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Five Views on Values and Technology

KARL E. SCHEIBE

Abstract—This paper describes four common postures in writings on values and technology. These are called: the Luddite, the technocratic, the apocalyptic, and the "cautionary moral sermon." These positions are considered to be legitimate, but lacking in both instrumental significance or adequacy of their conceptualizations of human values. A discussion of values in the framework of a rudimentary decision theory is then presented. This leads to a consideration of several paradoxes involving values—one based on the dimension of time, another based on the shift from individual to collective values, and the third based on the exchange of one type of value for another as problems are solved. These paradoxes are offered as partial justification for a fifth perspective on the relation between values and technology: that of the "curious, hopeful, and sometimes astonished observer."

INTRODUCTION

WRITINGS on values and technology seem to me to fall into several categories, all of which I want to avoid if only because each category is already well visited. I have forced four such categories into existence and have affixed to each a label. These are: the Luddite, the technocratic, the apocalyptic, and the cautionary moral sermon. After a brief description of each of these, I would like to describe my own perspective on the problem, which I will call that of the curious, hopeful, and sometimes astonished observer.

The Luddite

The basic premise of writers in this category is that technological development is inevitably and fundamentally dehumanizing and corrupting. In a technologically developed society, man is forced to live in a way that is both unnatural and spiritually depraved. A common specter is that of short-sighted little men, usually engineers and profiteering businessmen, who have taken over spaceship earth and are mindlessly extinguishing all human values. But there is hope. Charles Reich foresees a spontaneous emergence of a new post-technological mentality which will restore human authenticity. Theodore Roszak sees hope in the development of an anti-technological counterculture.

The Technocratic

Skinner [11] asserts that technology is our strength and that if we want to survive we must play from strength. Technology is on the march, and man must adapt to it. Science is accepted as universal ethic, not just a method for finding the truth. But the admixture of outmoded, traditional, quasi-religious ways of thinking and the scientific sophisticated, correct way of thinking about man has produced the inefficient and potentially disastrous custom of "muddling through." We must clean up our thinking, design our futures, and control that which we can control, which, thanks to technology, is just about everything.

The Apocalyptic

This perspective has much in common with that of the Luddites. Both hold that man has created the means of his own destruction through the exercise of his rational powers. However, the apocalyptic vision does not share the belief that technological development can be stopped or that man will spontaneously reject the insane world he has created and return to pastoral innocence. Scientists, who are still engaged in the pursuit of saving truths, are not likely to act as prophets of despair—it is incompatible with the requirements of their role. Instead, this view gains clearest expression from critics, such as Leslie Fiedler and Ihab Hassan, novelists and filmmakers, such as Kurt Vonnegut and Stanley Kubrick. Other writers, such as Paul Ehrlich and Alan Toffler, present visions of the future which seem almost as hopeless, though they may continue to express the belief that there is *a way out*. The one shred of hope presented in this perspective is that perhaps the apocalypse will act as a massive cultural electric-shock treatment. Possibly, when the dust settles, the remainder of mankind will live a long while before creating another massive disaster.

The Cautionary Moral Sermon

The most common practitioners of this art form are scientists themselves, who for one reason or another look up from their laboratory benches and are alarmed by what they see. The list of practitioners reads like an honor roll of science—Rene Dubos, Jacques Monod, George Wald, Linus Pauling, Garret Hardin, John Platt, J. Bronowski. The common theme is that scientists have been naive and unwittingly irresponsible in the pursuit of their calling. They have been on the glimmering path of truth and have trusted to politicians to run the world and to the social scientists to keep score and offer practical advice. Now it is clear that scientists have misplaced their trust. They must rekindle their humane values and must play a crucial role in creation of a new and more benevolent world order. With Whitehead [12], scientists must recognize that "Mankind has raised the edifice of science, because they have judged it worthwhile." Science is value-laden in origin and

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effect, and it is up to scientists to redeem the trust humanity has placed in them by dedicating themselves to the highest human values.

Another Perspective: The Curious, Hopeful, and Sometimes Astonished Observer

I do not mean to treat these perspectives on the question of value and technology with disrespect. In fact, I think there is considerable merit in each of them. But I have a general dissatisfaction with them on two counts. First, the practical benefit for human society of such considerations is not demonstrably great. A second and related difficulty is that each perspective contains presuppositions about human values which strike me as psychologically naive.

Academicians are capable of considerable self-deception when it comes to considering the impact of their ideas and discoveries. Noting the spate of scholarly works on nationalism, a subject not irrelevant to the topic at hand; Kedourie [7, p. 125] notes:

> It is absurd to think that professors of linguistics and collectors of folklore can do the work of statesmen and soldiers. What does happen is that academic enquiries are used by conflicting interests to bolster up their claims, and their results prevail. He who exercises power, exercises it while he can and as he can, and if he ceases to exercise power, then he ceases to rule. Academic research does not add a jot or a tittle to the capacity for ruling, and to pretend otherwise is to hide with equivocation what is a very clear matter.

At another point, Kedourie [7, p. 50] observes, "It is not philosophers who become kings, but kings who tame philosophy to their use." *Mutatis mutandis* this is also true for science.

My point is that knowledge is not necessarily power, nor does an enlightened perspective automatically attract the sympathetic cooperation of those in positions of social and political power. While we are occupied in talk about the evaluative implications of technology, our efforts are mocked by the force of events in the political and social realm. Lots of sensible plans exist for saving men from the negative effects of technological development—pollution, over-population, dissatisfaction with meaningless, repetitious labor, the arms race. But having a plan and being able to implement a plan are very different things. Skinner's plan for survival could just work, though I doubt its technical efficacy. But even if it were a great plan, somebody would first have to give massive political power to the Skinnerians, and this is an unlikely prospect. It is the beginning of wisdom about values to recognize that people do not always do what is good for them, even if they see the consequences of their actions very clearly.

This brings me to my second reservation about the common perspectives on the question of values and technology. They do not evince even this rudimentary insight into the values that direct human behavior. A positivistic scheme for a sane world order is all well and good, but such a scheme arouses little passion. Instead, there is power in more mysterious doctrines. Leninism, it has been said, has the twin virtues of "simultaneously blurring the mind while guiding the feet." In certain circumstances, under certain conditions, men will heed their prophets. However, scientific training has hardly been a strong suit of the effective prophets of the past. "When a society starts to feel itself hemmed in by evil portents, whether they come as social unease, saber rattling, or erratic Dow–Jones averages, there will always be someone with a faraway look in his bright eyes, shouting, 'This way out!' And many of us tend to follow along because at least *he* seems to know where he's going. Therein lies the timeless appeal of psychic prophecy," [13]. But by some means, effective prophets have acquired a good functional understanding of human values.

This point has not gone unrecognized. In commenting on the work of two recent panels assessing the impact of new technology, one run by the National Academy of Sciences, the other by the Institute for the Future, J. Bronowski [2, p. 199] observes:

> What the panels guess about changes in physical and biological habits is as always bold and stimulating; but what they say about the effect of such changes on personal and social psychology is as always meager, old-womanish, and painfully vague.

I assume that it is in recognition of this kind of criticism that a psychologist interested in values was asked to participate in this workshop. I also suspect that what I have to say about values and technology will decrease rather than increase your sense of certainty about the topic.

As a student of human values, I find my most legitimate stance to be that of the "curious, hopeful, and sometimes astonished observer," and it is this perspective which I assume for the present discussion. Much is to be learned about the origins and operation of human values, but the learning will come from observation, not from prioristic theoretical conceptions about what values must be. Like all scientists, the student of values must be hopeful that his observations will be of positive use. But, if I may hark back to the earlier point about the differences between knowledge and power, it is important to distinguish between hopes and realistic expectations about what the future might bring. Finally, if the observer is honest and if he observes widely enough, he will discover facts about values which are truly astonishing, or at the very least deeply puzzling.

The next section presents a rudimentary conception of values in a psychological framework. This will be followed by a consideration of three sets of observations about human values, each of which is both puzzling and highly relevant to the question of evaluating the impact of technological development.

A PSYCHOLOGICAL CONCEPTION OF THE GENESIS AND OPERATION OF VALUES

A few years ago I wrote a little book [10], which major premise is both useful and interesting to conceptualize at least some human behavior as following from individual beliefs and values. The two key terms are related to two major areas of psychological research and theory—cognition and motivation. Also, the terms beliefs and values are related in a generic way to two subdivisions of philosophical inquiry, epistemology and ethics. What a man does is conceived as depending both upon what he believes (expects, knows, suspects) and what he values (wants, desires, prefers).

Admittedly, such a conceptualization is highly schematic and crude; indeed, even if developed it turns out that there are many important psychological questions which simply cannot or should not be approached in this way. But if one is to undertake a discussion of values, it is important to recognize the logistic position of values in a full behavior theory.

A clear paradigm is afforded by modern decision theories of both descriptive and normative varieties. All such theories contain a variable that is cognate to value and all contain a variable that is cognate to belief. It is also common to all such theories that choices, decisions, or behaviors are presumed to result from some combination of motivational and cognitive antecedents. In simple gambling games, for instance, choice of play is presumed to depend upon the expectancy of success associated with each outcome and the positive or negative payoff of each outcome. In normative terms, the expected value of each bet can be readily calculated for all well-defined games. In descriptive terms, a major psychological scaling problem exists in understanding how individual expectancies and utilities are functionally related to the objective odds and payoffs.

The fundamental operation for defining values in this approach relies upon the preference paradigm. Given a range of possible objects, events, or states of being, all of which are equally available to the subject (in this case expectancies are equivalent for all options), the relative frequency of choice among options is supposed to reflect the relative values of the subject for the objects, events, or states of being in the array. As we shall see later, some fundamental problems are submerged by this method of operationalizing values. However, it should be clear that the preference paradigm is the major way of closing the conceptual gap between values and behavior.

If decision theories offer a way of conceptualizing the relationship of values to behavior, they do so by incorporating certain facilitative assumptions about the nature of values. It is generally assumed, for example, that values are where you find them—preference hierarchies are assumed as given, and the problem of the genesis of values is simply avoided. The question of how values are translated into behavior is only one of the concerns of the motivational psychologist. The other question is that of genesis or development. How do evaluative dispositions come to be what they are? What are the antecedents for the development of human motives?

At one time the stock answers for this sort of question were taken from the instinct psychologies. Post-Darwinian thinkers of the 19th century were ready to consider human beings as motivated by the same sorts of instinctive dispositions as were thought to control lower animals. However, the behaviorist-empiricist revolution in 20th century American psychology led to a rejection of this sort of explanation. In its place, great emphasis was placed on the processes of learning and conditioning. The second law of thermodynamics, leading in physiology to the principle of homeostasis, led in psychology to the proposition that all behavior is drive-reducing. This principle, together with the principles of association borrowed from the British empiricists, led to apparent theoretical solutions to both the performance and the development problems of motivation. Behavior results from a state of disequilibrium and is directed to a reestablishment of equilibrium. The sorts of stimulus events which can lead to disequilibrium and the kinds of motoric performances which are instrumental to the reestablishment of equilibrium were acquired through associative learning.

It would take us far afield to consider the controversies to which psychology was led by this general point of view. Suffice it to say for the present that the old instinct doctrines have never again enjoyed the use they once had in answers to the question of where values come from. However, the empiricist doctrine of associationism which replaced instinct theory has come upon evil days as an adequate theoretical base for responding to the same question. Some of my colleagues will still disagree, but I believe it correct to assert that both instinct theory and classical learning theories have failed as attempts to account for the origins of human values.

But the question of the origins of values is still a very lively one. In contemporary psychology, research and theory on this problem comes under the heading of socialization. The human infant is born as a social innocent but comes in the course of development to manifest an entire range of tastes, preferences, passions, desires, and moral principles as a product of his continual interaction with societal influences. Freud suggested that the major mechanism of socialization is identification, whereby the child comes to introject the moral standards and values of his parents. More modern theorists and researchers, from G. H. Mead to Jean Piaget and Lawrence Kohlberg, consider that a child develops through a series of stages in the process of socialization which correspond in part to the stages of his cognitive or intellectual development. The sources of internalized norms and values are considered to be not only parents, but peers, social reference groups, and idealized ethical systems.

For the present discussion it is sufficient to recognize that there is in contemporary psychology a great amount of theoretical and research activity on the problem of socialization—on the problem of how individuals come to acquire the values that regulate their social behavior.

For example, a number of monographs have appeared on the problem of political socialization, where the concern is to describe the way in which a child comes to evaluate political figures, institutions, doctrines, and opportunities for political activity [3], [5], [6]. This line of research has received a great impetus recently from recognition of the evident fact that political socialization in the United States does not appear to be working very well. Dissent and radical attempts to reform the political order certainly seem to be manifestation of social values, but they are not the sorts of values which those who manage the current system would recognize as the most admirable ones.

Another example of research on socialization is provided by Bandura [1] and his students at Stanford University. Children are allowed to observe the stylized behavior of models in novel situations, and are observed on subsequent occasions to demonstrate themselves the sorts of behavior they have observed. The acquisition of social values is shown to take place by observational or vicarious experience and can be accomplished in a single trial. The evidence for the effects of observed violence on television upon exhibited aggression is one of the products of this line of research. While Bandura and others who are working on the problem continue to explore the conditions under which this effect occurs, we may take it as established that socialization proceeds in part through the assimilation of vicarious experience and is not merely a matter of higher order conditioning.

Obviously, in the modern world the range of value models which is actually or potentially available to developing individuals is very large. One of the most impressive products of advanced technology is the capacity to exhibit remote occurrences to the developing person. The visibility of humanity to humanity is increasing tremendously. This introduces the possibility that the process of socialization will occur in a far less predictable way in the future than it has in the past, where a much more limited set of value models were available for possible adoption. The general norms of freedom of access to information and individual freedom of choice in soliciting information produce consequences which are inimical to a consistently and efficiently socialized social order.

A case is currently pending in the state of Wisconsin concerning the control which an Amish sect may maintain over the education of their children. The Amish provide their own schooling for their children through the eighth grade, but do not send them to school thereafter. The state of Wisconsin has a general statute requiring all children to attend school until age sixteen, and has brought suit against the Amish in an effort to send the children to public high schools. The prosecutor for the state argues that the children are being forcibly oppressed and that the state of Wisconsin has a responsibility to liberate these children by exposing them to the range of values which non-Amish Western culture has to present. But the Amish know that control of information is control of socialization. For the sake of their own cultural survival, they cannot afford to take chances with freedom of information and freedom of choice [14].

Similar restrictions of information are practiced by the regimes of South Africa, where television is prohibited, and China, where until recently, Mao's bamboo curtain effectively shielded the people of China from the opportunity to assimilate by observation the corrupting values of the West.

In our society we have been socialized to the proposition that knowledge is good, freedom is good, individual choice is good, technological progress is good. Our decisions as individuals and as a society have been strongly influenced by these values. Indeed, the message of the cautionary moral sermon is that these kinds of values *should* be applied to our decision matrices. It is my objective in the remainder of this paper to show how the implantation of these perfectly admirable values leads to unintended and, from my perspective, highly undesirable consequences.

THE VALUE PARADOX POSED BY TIME, OR WHEN ARE THE CHIPS CASHED IN

Decision theorists consider only those choice situations which can be mapped and which are bounded in time. Similarly, in cost-benefit analyses of proposed projects or technical developments, a time horizon must be established. But the arbitrary establishment of time boundaries produces a disjunction between the decision model and the real world. Second, third, and higher order consequences of chosen courses of action continue to be realized into the indefinite future. Because these consequences are not evaluatively neutral, the initial solution to the decision problem may yield paradoxical and nonmaximal consequences.

Considerable psychological research has been done on the problem of delay of gratification [8]. Experimental situations are devised such that a subject may accept a small reward now or a larger reward later. This research has established the existence of consistent individual differences in the capacity to delay gratification. Some individuals seem to make decisions in a larger framework of time than others.

The functional relationship between time and utility is, of course, included in the analysis of technological feasibility studies. Some developments are explicitly designed to yield short-term benefits, which in the longer run produce negatively valued outcomes. For example, the development of efficient mass-production techniques for manufactured articles yields relatively immediate benefits. However, the long-term consequences, such as worker and consumer boredom and rapid diminution of raw materials will eventually be realized, and in such a way as to make questionable the wisdom of initially opting for the techniques of mass production. Clearly, different companies and different nations differ in the extent to which they try to include long-term consequences in their decision matrix.

One of the most ambitious technological projects of the post-war era is being executed in Brazil [15]. A 3000-mile highway is being cut through the Amazon jungle, in an attempt to open up the heart of the South American continent for development. Obviously, the decision of the Brazilian government to build this highway is a bold one. It entails the assumption of weighty short-term sacrifices—diversion of capital and technological expertise from other possible projects. However, Brazilian technocrats are confident of the long-term benefits of the completed project. Access to new land, new raw materials, provision of new opportunities for the starving people of the arid Northeast of Brazil, as well as the less tangible benefit of building national pride are reasonable objectives in the long run for Brazil. However, the consequences of this project will not stop suddenly with the realization of these objectives. The Amazon rain forest produces a sizable proportion of the world's oxygen. Will the development of the Amazon region endanger this supply? The development of Brazil as a major economic power is already being perceived as a threat by other nations in Latin America. Brazil has in the past 150 years had only one war with a neighboring country. Will the increased power of Brazil bring about new Latin American wars? Will the present precarious balance of power in the world be upset by the emergence of a new super-power, which the Trans-Amazon highway will facilitate?

Merely suggesting these possible long-term consequences is likely to lead foreign observers to wish Brazil to go slowly with its development. From our perspective, there may be the additional hazard that the technical and economic development of Brazil may mean the end of one of the most delightful tourist attractions on earth.

THE INDIVIDUAL-COLLECTIVITY VALUE PARADOX

We may now see a relation between the time paradox and the problem which Hardin [4] has aptly called, "The tragedy of the commons." Hardin demonstrates that individual prudence may inexorably produce collective disaster. As the limits of scarce resources are approached by mass development and consumption, the benevolent invisible hand of Adam Smith may turn into a device of mass strangulation.

Obviously, it is in the interests of all of the more than 150 nations on earth to seek technological development. The modern media act as our missionaries, only they do the job much more efficiently. Without question, the underdeveloped nations of the world want what we have, they can see the images of our products and our techniques very clearly. We may attempt a cautionary moral sermon to the effect that our own society is in deep trouble—that the technological problems we have solved have left in their wake much more difficult problems—despair, the mindless urge to destroy, pervasive psychoneurotic difficulties. The cautionary moral sermon will have no effect. It is as if the neighboring farmer urges you not to add another cow to graze on the commons because he can attest that a big herd like the one he has brings nothing but headaches.

Our attempts to tell smaller nations that they should not develop a nuclear arsenal, in the interests of the collectivity, are of a similar kind. It is obvious that power matters in international relations. If you do not have power you are not getting as much respect as you might if you did have power. Result: It is in the interests of every nation to develop its nuclear capability. Of course, the result is collective disaster.

The point is that it is difficult to get an individual or a collective entity socialized to the interests and values of their competitors, so that when *they* make decisions, they will take *our* values into consideration. In order to accomplish this, to revert to an earlier point, socialization to collective interests must be controlled and directed. But if socialization to collective interests is truly to be controlled and directed, we must establish not only a world government, but a world government which does *not* give ultimate value to knowledge, freedom of inquiry, individual choice, and technological progress.

Nobody wishes to do this. We have steadily resisted attempts at tyrannical collectivization in this century, and we are likely to continue to do so. But in the meantime, the inexorable tragedy of the commons is working towards its last act. Erlich's population bomb is ticking. Nine million new automobiles continue to appear each year as testimony to our veneration for freedom of choice. Wars of "liberation" continue, so that newly liberated peoples can aspire to the same kind of material affluence which Americans are finding to be so stale and tasteless. These are some observations about human values which the student may find astonishing or puzzling.

THE CHIMERA OF PROBLEM SOLVING

Both of the preceding value problems may be considered problems of extension. For the first, extending the dimension of time yields paradoxical transformations of decision payoffs. For the second, extension from the individual to the collectivity produces unanticipated transvaluations. I wish to close by mentioning a third value-paradox—one that is a problem of intension rather than extension. I refer to the problem of intrapsychic value conflicts.

While one may not agree with Freud about the instinctual origins of the problem, abundant evidence exists for the proposition that man is at war with himself, that he does not have unequivocal values, that the solution to what he thinks of as his problems only produces other problems.

I wish to resort to a quotation from Orwell [9, p. 163] which illustrates very well the sort of paradox I have in mind:

> If you look into your own mind, which are you: Don Quixote or Sancho Panza? Almost certainly you are both. There is one part of you that wishes to be a hero or a saint, but another part of you is a little fat man who sees very clearly the advantages of staying alive with a whole skin. He is your unofficial self—the voice of the belly protesting against the soul. His tastes lie towards safety, soft beds, no work, pots of beer and women with 'voluptuous' figures. He it is who punctures your fine attitudes and urges you to look after Number One, to be unfaithful to your wife, to bilk your debts, and so on and so forth. Whether you allow yourself to be influenced by him is a different question. But it is simply a lie to say that he is not part of you, just as it is a lie to say that Don Quixote is not part of you either, though most of what is said and written consists of one lie or the other, usually the first.

If this sort of speculation has merit, and I consider that it does, then it yields an interesting conclusion when put together with the observation that technology can only solve problems of the Sancho Panza variety. The conclusion is that technical solutions do not really solve a person's problems—they merely transfer the problem to a different aspect of self. When a person's belly is empty his overwhelming problem is well defined, and it has a technical solution. But when his belly is full, he may have leisure to pursue a depressing series of thoughts about the significance of his efforts, the meaning of his life. "What are people for," asks one of Kurt Vonnegut's characters just before he commits suicide. Such a question would not occur to someone struggling to live.

My final observation, then, is that technical problems admit of technical solutions, but that these solutions will inevitably produce additional psychological problems—not so much deficit problems as identity problems. When individuals feel an identity problem coming on, they may retreat from it, but only at the cost of creating for themselves living problems of a more technical kind. Thus we see the modern phenomenon of the high level drop-out, the professional man who opts out, chucks it all and joins a rural commune. I do not see that kind of regressive role transformation as a solution to the society's problems, but rather as an indication of the nature of those problems.

As a final note of observation, I must confess that I can see no clearly realizable solution to such problems as overpopulation, pollution, the nuclear arms race, diminution of national resources, or the less tangible problems of loss of identity and cultural despair. I expect that we will continue to trade these problems for each other. But I am astonished because I remain hopeful about that which I do not see.

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Vision, Faith, and Knowledge

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Abstract—The authors discuss the general relationships between technology and personal and social values. They attempt to stimulate consideration by individuals and societies of the changing judgments and ethics now required both for the engineering profession and individual engineers.

They suggest that values and actions in the social environment are symbolic and that most of our present institutions are responsive to an environment of the rather distant past. Laissez-faire, the Adam Smith "hidden hand," and "caveat emptor" no longer can be the guiding principles of a technology or of an affluent social system.

TWO HUNDRED years ago Adam Smith articulated an ingenious explanation to an uncomfortable problem. He theorized that individual economic action taken to maximize personal utility would, through a process of coordination by an "Unseen Hand," lead to a maximization of the collective good. Important as this theory has been in our economic history, it is not clear whether its wide acceptance has been due to its empirical accuracy or to its intellectual comfort. What a reassuring thought it is to consider that the more selfish and narrowminded we are, the more we are furthering the public interest.

Today, in an era of vast corporations, external diseconomies, and a high degree of complexity and interdependency, one might well wonder where our faith in this mystical Unseen Hand has led us. For many of us the peace and comfort of a belief in the universal harmony between

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the individual and the cosmos have been shattered by a new awareness of unintended evil. The unaccounted-for consequences of economic and technical activity are becoming increasingly inescapable. Air, noise, and water pollution foul our natural resources, and our central cities are in many cases rapidly becoming unlivable.

The impact of these consequences has been to cause some moral questioning, and much name-calling and castigation. Who is to blame for our current situation? Whose fault is pollution? Whose responsibility is its alleviation? Who is to blame for unsafe automobiles? After all, remember *caveat emptor*. Is the government the sole protector of the public good, leaving individuals to maximize their self-interest? What responsibilities do you have as citizens, as engineers employed by a corporation, as members of a profession, and as political and economic leaders?

We are not so presumptuous as to pretend to be able to answer any of these questions, and we should all be sceptical of any attempt we should make. We can together, however, search for ways to think about such problems in order to find constructive ways of conceptualizing ethical problems so that they are more amenable to clear thinking, rather than merely losing sleep over them or ascribing blame to someone else so that we can go to sleep more easily.

The phenomenon of unintended detrimental consequences in the large, due to actions taken in the small, is of course not new. Cities have had to cope with the problem of garbage collection for centuries, and the questions of responsibility have been pondered since such problems were recognized; the Socratic dialogues are full of exactly the type of moral questions which have been raised here.

What, then, is different about our times? Why should we feel the need to come together here and now to talk about our mutual concern? First, a number of changes have taken place in our culture during the past fifty years or so which increase our awareness of these problems and give an urgency to the need for solutions to them. The frontier is gone and the consequences of economic activity (for example, depletion of natural resources) can no longer be alleviated by a deeper penetration into the hinterlands. Moreover, the system is vastly more complex and its subsystems more interdependent. As a consequence of these two factors, the impact of changes in the system, both beneficial and detrimental, is felt much more quickly and more severely than earlier in our history. Communication and transportation systems are far more sophisticated, allowing us to be aware of many parts of the system simultaneously and able to recognize their interconnections.

Another important change which is quite recent involves the perception of our position in the Industrial Revolution and our relative level of affluence. We can now afford to look around us and ponder what we have wrought, both in terms of time and money. We are no longer a young country in a hurry to make things and get places. We are older, more mature, and in a new way feeling responsibility for "ourselves and our posterity."

Let us then begin to look at the relation between technology and value or, more precisely, technology and ethics. We choose the term ethics because it refers to both aspects of moral consideration: value, good and bad; and obligation, right and wrong (i.e., roses which smell sweetly are to be valued, but we ought not to use them to make soup).

Notice that Adam Smith's formulation of the relation between individual self-interest and the collective good requires a distinction between two moral perspectives—two ways of looking at value and obligation. The first is individual—personal goals and motivations designed to maximize individual satisfaction. The second is collective—a perspective which considers benefits which accrue to the people in general, not to anyone in particular. Smith's theory proposed a correlation between these two calculations of good (value): the more individuals maximize their individual good, the more the public good is promoted. It is precisely this correlation which has now been called into question and which serves as the fundamental question for this conference: what is the relation between individual economic and technical action and the general welfare, and what can be done to adjust this relation to further the public good?

Delving further into this problem, utilizing this distinction between in-out (individual) and out-in (collective) ethical perspectives, let us distinguish between two types of reform proposals. The first accepts the Smithian (or, more accurately, Hobbesian) formulation of the self-seeking nature of man. The proposals according to this perspective are essentially manipulation of economic institutions in order to bring about the coordination for which the Hand is unseen (for example, Milton Friedman taxing pollution). The second type of proposal for reform is founded upon the hope that the nature of man can be changed by instituting new economic relationships, and by a system of propaganda which encourages business and technical people to consider their social responsibility. Note that the difference between these two approaches is not one of ultimate ends—that is, they often agree concerning the determination of the general welfare. Rather, they disagree as to the malleability of man's nature—the former asserting that it must be assumed to be constant over time and self-seeking in character, and the latter asserting that it can be changed for the better.

It follows from this distinction between two types of reform that there are, correspondingly, two formulations of the moral responsibility of the consequences of the economic and technical system. The first (fixed nature of man) argues that since man is by nature self-seeking, it cannot be his responsibility to change his calculations of cost and benefit to include public considerations. It is thus the responsibility of the government to compel or arrange such considerations of the public welfare. Rousseau articulated this position with his classic formulation of the stag hunt. In this formulation he supposes that ten men want to organize themselves for the purposes of hunting a stag. They agree that if one of them finds a stag, he will call to the others, and together they will have a greater chance of killing him. However, during the hunt, one man spots a hare. According to his calculation of individual gain, this man would follow the hare and thereby gain more than what his share of the stag might be. Thus, some system of authority is necessary to ensure collective gain in the face of individual calculations of personal benefits. It is the responsibility of the men who compose this government to "provide for the common defense, promote the general welfare." The other type of reform position ascribes moral responsibility to the individual actors in the system, asserting that, in addition to individual calculators of personal gain, they are citizens of a collectivity. As such, they have a responsibility to consider the public welfare in their individual decisions. Con Edison, according to this view, should (i.e., has the moral responsibility to) consider the cost to the locale of their pollution of the Hudson River when they propose to build their new hydroelectric generator.

Just as there is divergence of opinion as to the malleability of the nature of man and the proper ascription of moral responsibility, there is also divergence as to the relationship between individual motivation and institutional imperatives. One point of view claims that the motivations of economic actors are determined by institutional incentives (he who is self-aggrandizing gets ahead). Marxists, for example, argue that the acquisitive, manipulative, materialistic nature of modern economic man is due to the nature of labor relations and, more broadly, the capitalist system. According to this view it is pointless to try to change the nature of man (e.g., encourage him to consider his broader social responsibilities) because it is the economic system per se which determines the motivations of his actions. Rather, the economic institutions and relations themselves must be changed. Another view asserts that it is man's "real" nature which is drawn upon by the system. In this case, it is pointless to attempt to change economic motivations and incentives by manipulating the institutional relationships or by using some form of propaganda, since those motivations are innate in man's character and will be operative in any system. Ralph Nader, for example, does not argue for a propaganda campaign to encourage corporation policymakers to consider their social responsibility for the broader consequences of their individual actions. Rather, he acts as a watchdog for the general welfare, barking loudly when the corporation thief comes trespassing on the posted ground of consumer welfare.

Thus we can make two formulations of the problem of moral responsibility in our post-Smithian world, and two corresponding proposals for reform. The first asserts that it is man's fundamental nature to be self-seeking, that his decisions will always be made on the grounds of individual utility maximization. Accordingly, the only hope for alleviating the current problems which arise from the nonexistent Hand (i.e., the divergence between individual and system rationality) is to manipulate institutional relationships and incentives to ensure the protection of the general welfare. The second position asserts that man's nature is more malleable, and economic actors can be convinced of the wisdom of acting in accordance with the public interest rather than constantly seeking individual gain.

Consequently, these two views can be distinguished along three dimensions: 1) the malleability of man's nature (changeable or not, determined by economic institutions or not); 2) the corresponding view of moral responsibility (government or citizen); 3) the method of reform (institutional manipulation or moralistic propaganda).

Now that these two ideal-typical views have been conceptually distinguished from one another, we should like to proceed to consider some of the territory between these two polar extremes. We are sceptical of monocausal anthropological explanations of social phenomena. For example, both those who assert that certain innate characteristics of man's nature "determine" economic institutions, and those who assert that those institutions "determine" man's nature and motivations oversimplify the symbiotic correlative nature of the relationship between personality and cultural institutions. An ecological perspective of this interrelationship might perhaps be more elucidating. In the case of man, the organism responds to changes in its environment by adaptation but at the same time can manipulate certain changes in its environment. For example, when man first developed agricultural tools, they allowed him to manipulate his environment. However, the new environment created new pressures for adaptation in terms of social organization, which in turn created new possibilities for manipulation of the environment. Each element in the ecological system affects each other element symbiotically. Thus one cannot determine causal primacy since the changes are mutually causative.

Another view of the relationship between institutional structures and economic incentive is seen in what we might call the "after you, Alfonse" problem. In this view the incentive for change is seen as already existing within the personalities of the members of industry, but the economic structure and the legal framework within which they operate prevents them from changing their behavior accordingly. For example, the automobile manufacturers claimed that they were quite willing to design and build safer cars, but two factors prevented them: the public was not interested in safer cars, and antitrust laws prevented their combining their research development resources. According to this view there existed a situation in which each firm was willing to change its pattern of behavior if the other firms did so at the same time. Yet each firm was unwilling to go first, since by doing so it would be committing economic suicide, or so they felt. Hence—after you, Alfonse.

The response of government to this situation was to mandate safety standards which allowed the automobile manufacturers to offer safety features simultaneously. This is an intriguing view of the problem of values in the context of the economic structure since it asserts that the motivations for change are present, but the institutions thwart their realization as changed action. This is in juxtaposition to the views articulated earlier which asserted that it is the institutions which mold the motivations of the actors in the economic system, and that one must change their basic self-aggrandizing motivations either by propaganda or structural reform.

MORE BASIC CONSIDERATIONS

> The unprecedented power given mankind by a science-based technology places him in a race between Utopia and oblivion.
>
> *Carl Madden, Chief Economist*
> *U.S. Chamber of Commerce*

> [Systems simulations] give indications that suggest corrective action will often be ineffective or even adverse in its results . . . choosing an ineffective or detrimental policy for coping with a complex system is not a mere matter of random choice. The intuitive process will select the wrong solution more often than not.
>
> *Jay Forrester*
> *Massachusetts Institute of Technology, Cambridge, Mass.*

> What is needed, but lacking, is a set of procedures to enable consideration of social utility and of scientific merit to be fused in both the design of institutions and the process of public policy.
>
> *Carl Madden*

Underlying the concern with pollution, ghetto slums, unsafe automobiles, and robot assembly-line workmen is a much more general loss of faith. Somehow what was good and holy—the work ethic, the efficacy of technology to solve social problems—is no longer to be unquestionably revered. It is a rude awakening to many that the totem of technology has not worked its magic. This is in its deepest sense not a crisis of economic values at all—it is a religious crisis. Beliefs which have been deeply held and cherished are being smashed by our nation's iconoclastic youth. Our condition is not only one of confusion and malaise, it is one of anguish.

What is the nature of this religious questioning? What are the old values? What are the new ones being recommended to take their place? What changes in belief are called for, and why? Are there conditions which mandate change at this deeply personal level? We should perhaps approach this confusing and emotionally charged area of concern 1) with a language with which we can name intellectual concepts and communicate with one another with less chance of misinterpretation; and 2) from an historical perspective in order to view the present situation in its appropriate chronological context.

We think the current scepticism of our industrial system felt by much of the youth of the country and by many of the more thoughtful members of the "establishment" finds its focus in two basic tenets of the industrial–technological spirit. The first is scientism—the religious belief in the efficacy of science and technology to solve problems, advance mankind, and bring "progress." There is of course much evidence to support this view, but for most of us it has a very large affective or emotional component as well. Scientism is the belief that technological development is efficacious and beneficial.

The second fundamental tenet of the spirit of Western industrialism is individualism, the belief that cultural and technological advancement takes place most rapidly and beneficially when members of the culture work individually and independently. This type of activity maximizes the chances of innovation, clear thinking, and human creativity. As Max Weber argues with such insight, the rise of the spirit of capitalism came about in Calvinist Germany following the Protestant Reformation, which restored the direct link between individual men and their God. Through faith and work, individuals could obtain salvation through God's efficacious grace. This ethic was in opposition to the previous ethic of traditionalism—the acceptance of the institutionalized church as the link between man and God. Protestantism was ascetic (self-denying), nonvirtuosic (individuals could through their own efforts obtain salvation), and rationalistic (the meaning of the universe was understandable; purposive action could be taken, as opposed to the previous belief in the magical, the mysterious, and the traditional institution of the collectivity).

Weber asserts that it was precisely this Protestant ethic which served as the underlying spirit of capitalism and industrial development. In more simple language, it meant that individuals did the work that was before them; they did their job. Such was the highest form of human endeavor. If men worked at the tasks before them and lived a self-denying, conscientious life, they maximized their chances of going to heaven at the same time as they worked for the good of their culture. Thus the ethic was essentially this-worldly—involving a correlation between the religious and the secular—as opposed to almost every other major religion which involves a separation between this world and the next—between actions taken for personal material benefit and actions taken for spiritual benefit.

Combine this new Protestant ethic with the Smithian view of the ultimate collective benefits of individual economic action and one can begin to see both the power and the comfort of the new view of economic–technological behavior. Life was so simple. All we had to do was look out for our own interests and everything which we wanted in both this world and the next would result. All we had to do everyday was our jobs, and plod ahead doing our duties to God, self, and country, and we would advance science, culture, and ourself simultaneously. Such was the definition of progress—individualistic and self-aggrandizing, based on the efficacy of technological advances.

Now

Of course conditions have changed radically since the beginnings of the industrial revolution. But what changes affect this underlying faith in individualism and scientism, the Protestant–capitalist ethic? Why is it being questioned now? Essentially what has happened, and only within the last twenty years, is that the collective consequences of individual action are more easily perceived. The frontier is gone; land and other natural resources can no longer be conceived as inexhaustible, and the economic system of manufacturers, buyers, and sellers is now closed. Therefore, the feedback processes are apparent to all participants.

This new situation is much more significant than one might first think by merely listening to jeers of disgruntled students and the complaints of Ralph Nader. Individual action must be seen in an entirely different light. It is not

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enough simply to understand that the Smithian Unseen Hand can no longer be trusted. The interdependence of each component of the system is extremely difficult to isolate and comprehend. It is not at all clear what actions will in fact have beneficial consequences to the collectivity.

Some of these feedback processes are, of course, obvious. If Con Edison pours pollutants into the Hudson River, the citizens along the river suffer. They suffer in a way which is not considered by the industry in the individual calculus of profit and loss figures. This is an important point and one which must be considered seriously by all of us interested in public policy, guarding the public welfare, and enhancing the quality of life. However, the situation in our complex and interdependent world is far more subtle, and the assumptions of scientism and individualism must be questioned for different reasons than simply to avoid negative externalities. Consider the following example of purposive action—that is, action which appears to be rational (remember the rationalism of the Protestant ethic), appears to be taken to achieve a desired result. A town seeks to have the congestion of a road relieved. Accordingly, they widen the road to allow the freer passage of automobiles. However, since the road is now more attractive, more drivers choose to travel the road, and it becomes more congested than before.

This example of counterintuitive negative feedback describes many aspects of our current technological situation. As Jay Forrester is struggling to point out to policy-makers who still believe in their myopic intuition, building low-cost housing in the cities makes the situation worse, not better, since it makes the inner city relatively more attractive for precisely those people who suffer most from being in the city.

The same process of negative feedback can be seen in many other areas of public policy. The Medicaid and Medicare programs increased the ability of the poor to pay for health care. The response of the health industries (doctors, drug manufacturing industries, drug stores, etc.) was to raise the price of health care according to what the market would bear (as any student of the market system would tell you they would). Our foreign aid program sought to raise the health standards of underdeveloped countries by providing medicine to lower the infant mortality rate. Lowering the infant mortality rate increases the population, placing more demands on the health service facilities and thus lowers the standards of health care.

What Forrester says about interaction within a system is vitally important and compels us to rethink some of our most basic (and seemingly most obvious) philosophic assumptions about the efficacy of thought, purposive action, and the application of technology to problems. His statement quoted in the preceding section is revolutionary in the history of knowledge.

Let us try to tie together some of the strands of our argument which may appear somewhat bedraggled by now. Our society is in a situation of deep religious and philosophic significance. We are not convinced of this significance by listening to hippies or to Charles Reich or to R. D. Laing, although each sees something of the transitional nature of our times. Rather, the peculiarity of our predicament can be seen in its historical perspective from the understanding of its religious-philosophic significance—in other words, from an understanding of the relationship between the economic system and the ethical and epistemological tenets which serve as its grounding in the broader-meaning system of man. From the time of the Reformation through the Industrial Revolution to our present time there was a fit between the personality structure and the cultural institutions of economic actors. By this we mean that the personal-meaning system and motivations of individuals matched the incentives of the economic-technical system. Personal needs for meaning (religious as well as secular) were satisfied by the interaction of the economic and religious systems. Such was the relation of the Protestant ethic and the spirit of capitalism in Weber's sense. Individuals took efficacious action by doing their job, by being innovative, and by being self-aggrandizing, both in terms of personal meaning and in terms of the economic system. Concepts such as "achievement" and "progress" had definite and personally salient meaning. Problems were intrinsically solvable; to solve them simply took time, effort, and ingenuity. Life could grow better from day to day through work. And the evidence through feedback was that these people were right—technological advancement was fantastic in its pace and consequence. The standard of living rose more rapidly than at any other time in history. Transportation systems were built, and the system of interchangeable parts was developed, providing the technique for mass production. Wars were fought and won, and a depression was overcome through suffering and hard work.

These values which fit so neatly into the economic system are not called into question today simply because we have reached a technological plateau. The post-industrial society is not defined in terms of its relative affluence and the need for finding meaningful nonwork. Students today are not sceptical and iconoclastic simply because they are spoiled and mobile and do not feel the compulsion to work to support themselves. The economic system is not to be criticized simply because it results in negative diseconomies. Rather, these values are called into negative question because they are in fact no longer appropriate. What has been called into question is the fundamental belief that you can work at something (in the small) and accomplish what you set out to accomplish (in the large).

This doubt, which can lead to anguish at a very deep personal level, comes about because of two phenomena which are taking place simultaneously—the first in terms of cultural values, the second in terms of knowledge and action. The first phenomenon is the questioning of the personal rewards from the capitalist system. The result of achievement and material acquisition was supposed to be happiness and satisfaction. Well, here we are. Are we really happier because we are richer, or are meaning and satisfaction to be found in some other facet of human endeavor? This is one kind of questioning brought about by our technological progress. It involves the relation of action to value and meaning.

The second phenomenon involves the relation between action and knowledge. The systemic interactions through feedback of our society are now so inescapable and complex that they must be dealt with in an entirely new way. We cannot simply apply ourselves to a problem, based upon the faith that our working at it will somehow alleviate the difficulty. Our foreign policy and our urban policy, to name only two of the most obvious areas of public policy, have suffered because of precisely this type of myopic naiveté. Supporting a country militarily with the hope of making it more likely to become democratic is perhaps more often than not counterproductive, since the country becomes increasingly dependent upon the support, hence less capable of providing for itself, hence less capable of govèrning itself. Or, to use a previous example, building low-cost center-city housing can only serve to increase the congestion of the center city by making it more attractive to live there.

What is needed in response to the dual problems of action-value and action-knowledge is a different vision or the role of technology in our society. In the past, technological development was seen as an end in itself, a value to be pursued per se. It seemed obvious on the face of it that that progress meant Progress—i.e., technical advancement in the small meant progress in the large in terms of an increase in the quality of human life. We have tried to show that both views of that belief—the religious-personal and the scientific—are being subjected to the most basic scepticism because our condition in this complex, interdependent, affluent, and baffling society warrants it. Working at it, applying our technological know-how, does not necessarily get us closer to where we want to go.

Technology should be seen as a tool, as a means which can be utilized to achieve the values, independent of technology, that we decide we wish to realize. To take an action-knowledge example: if we wish to relieve the congestion on the town highway, the problem must be conceptualized as exactly that—the abatement of congestion on the highway. The task is not, as so many engineers would intuitively assert, to build a better highway. The answer to the congestion problem might be found in a quite different component of the interactive system (i.e., alternating work hours, building a rapid transit system, or digging pot holes in the road). Or, to take an action-value perspective, it must be recognized that the enterprise of technology is only a means to personal happiness and satisfaction which may or may not come as a result. The endeavor itself should not be confused with those human values which it seeks to realize. Expanding your division of General Motors is not good in itself; it is good only if it provides some good as a consequence (wives have more time to spend with their husbands because they have a second car, your expanded branch hires several currently-unemployed laborers, etc.).

If technology is seen simply as a means, not as an end in itself, and not good or bad in itself, what is the responsibility of engineers whose job it is to develop and apply technology? What are your responsibilities as a citizen, as a member of a profession, as a member of a firm, and as a human being to see that your technology has beneficial consequences? Do your various roles conflict? These questions are both serious and difficult, and cannot be answered in such a short paper. We would, however, like to consider several perspectives on the problem, hopefully shedding some new light on some of them.

The first view we would like to consider is that propounded by David Rockefeller and many others both in and out of "the establishment": the social responsibility of business. Rockefeller argues that businessmen are a part of their community; they take actions which have profound effects upon that community, and therefore have a responsibility to contribute to the solutions of the social problems of that community. Although we applaud its sentiment, we think this view involves a fundamental confusion concerning the role of business in our society. Businessmen *qua* businessmen have no such social responsibility. That is, there is nothing in the role of business which gives them that responsibility for the alleviation of social problems. It may be that as citizens of our society the members of business sectors may see some of the detrimental consequences of their behavior and some of the possibilities for beneficial action, and may take constructive action as a result of this vision—but they are acting as citizens, not as businessmen.

More important, however, we should look at the motivational basis of this approach. Businessmen should respond, argues Rockefeller, because they find the argument morally persuasive. It is possible that they will respond to this exhortation and be convinced, but there is no guarantee that they will. Here we return to the twofold distinction made at the beginning of this paper. We first distinguished between two strategies for reform: propaganda and incentive manipulation. Second, we showed that these two strategies were based upon differing views of the nature of man: the first assuming that men are changeable in their motivations, that they can be convinced of the wrongness of their action and will take steps to change their behavior for moral reasons; the second assuming that men always act to further their self-interests and, accordingly, it is these interests which they must be convinced to change.

What is the answer? How can you encourage the users of technology to understand and be responsible for its consequences? The answer we think depends upon your role in the society. As a citizen you should join Rockefeller in his exhortation, seeking to be as eloquent and persuasive as you can to convince members of the business community to become socially responsible. As policy-makers, however, your role is entirely different. In this role you are a social engineer who must construct and adjust a complex social–economic system and make certain heuristic assumptions about human behavior in order to be effective. That is, the policy-maker cannot rely on trust in the goodness of the human spirit to realize his objectives in terms of changes of behavior. Laws must be passed which make it in the self-interest of those to whom the law applies to adhere to rather than violate it.

The Founding Fathers understood this principle. With astounding insight and genius they constructed a system which would work even if the members did not trust one another and if they constantly sought their own advancement and not that of the country. It is a system in many ways based on mistrust, jealousy, and self-interest. Such is the vision of social engineers. And not because man is, in fact, untrustworthy and self-interested and unpersuaded by moral arguments, but because he must be treated as such in order to guarantee that the system will work. It must be assumed, to return to the example used by Rousseau, that each member of the hunting party will, in fact, chase after the hare even if he has promised not to do so. Because if there is no punishment, it will, in fact, be in his interest to do so and this will be recognized by the one or two self-interested men in the group. Thus, the argument about the real moral nature of man is irrelevant since, in order to guarantee that the system will work, man must be treated in any system as if he is self-interested.

Those of you whose role is social engineering in terms of policy formulation are advised to look to the manipulation of incentives rather than exhortation in order to encourage social responsibility. As members of the profession of engineering, however, it seems to me that your responsibility is quite different. The question here to be considered is: what role does engineering play in our transitional condition of action-value and action-knowledge? It appears that the current anxious situation finds its primary focus on this profession more than on any other. It is precisely because of the two aspects of the questioning of the Western industrial ethic that engineering must redefine itself. It is no longer enough for you to say that you are what you do, that, because you do technology, you are engineers. But to what end? If technology is really to be seen as a means to an end, should not the inventors of that technology understand the relation between means and ends? Is that not what engineering is about—the application of technology as a means to achieve some desired end? Therefore, the vision of the engineer cannot simply be confined to that problem which appears before him or which is thrust before him. Consider the example of the highway congestion. The responsibility of the engineer, it seems, is to explain to the policy-makers that widening the highway will bring about more congestion, not less. That is his job, since he understands the relationship between means and ends, and understands how to make the consequences of his action be in the direction of the ends he wishes to realize.

That is to say, engineers cannot simply be problem-solvers in the small (i.e., widening the highway). They must be problem-solvers in the large (relieving congestion). They must set themselves the task of understanding the nature of the interdependencies and feedback loops within the system with which they are dealing and be able to take intelligent responsible action. No one else can perform this role. All the other actors in the system—politicians, businessmen, consumers, etc.—are interested in solutions to problems in the small. There is no incentive for them to be concerned with problems in the large. As Russel Ackoff of the University of Pennsylvania states:

> In a real sense, problems do not exist. They are abstractions from real problems. The real situations from which they are abstracted are messes. A mess is a system of interacting problems. Planning should be concerned with messes. Not problems.
>
> The solution to a mess is not equal to the sum of the solutions to its parts. The solution to its parts should be derived from a solution to the whole: not vice versa. Science has provided powerful methods, techniques, and tools for solving problems, but it has provided little help in solving messes. . . . The question of priorities is misleading. All messes should be dealt with simultaneously and interactively.

Engineers, then, are not gadgeteers; they are consequence experts; they study and practice the control of consequences in a complex, interactive system. This task may be very simple in a simple system such as the design of an electric circuit, or very complex and subtle such as relieving some of the problems of the inner city. But the essential role is the same: the understanding and manipulation of the consequences of a certain set of actions in order to achieve a desired end. An engineer is a designer and a means expert.

There are many other issues which are vital in understanding the nature of the relationship between technology and human values. This paper is intended to provide an intellectual basis upon which to pursue such a discussion and to provide a conceptual framework within which the issues may be productively considered. It is clear that something is going on in our culture: we are in an important period of transition. Old values no longer seem appropriate. The efficacy of the capitalist system, the political system, and even of thought itself has been called into question. With a haranguing irreverent son around it is easy to feel guilty and without direction. We hope that we have been able to clear away some of the brambles which tear at your skin on this ethical journey, and to point out some of the trails along the way.

SOME THOUGHTS FROM SUBSEQUENT REREADING AND DISCUSSION

1) The use of the term "scientism" may be confusing, since it sometimes refers only to the application of the scientific method rather than to some quasi-religious belief in its ultimate efficacy. The two concepts should be kept distinct, since it is certainly possible to apply the scientific method to problems without having that method determine one's world view. That may very well be a likely tendency, however.

2) Related to the dual difficulties of looking at a problem only in the small and adopting a technique (means) as a religious world view (end), is the phenomenon of role identification. That is, many people in our society identify themselves emotionally and philosophically with their job or their role in the culture. Often, the first question asked of you when someone is first introduced to you is "What do you do?", as if what you do were related in some deep and determining sense to what you are as a person. Note how closely this cultural phenomenon is related to the ethical myopia of "I just do my job" (knowledge-value) and working at problems only in the small (knowledge-action).

3) One example of a counterintuitive approach to a currently pressing problem is that of energy production. Most engineers are looking to alternate sources of energy to cope with the problem of increased energy consumption. Perhaps we should consider using better insulation or fewer cars. Perhaps the real problem is not energy consumption and supply at all, but rather energy efficiency.

4) It is very important to realize that both strategies of reform (propaganda and manipulation of institutional incentives) are being practiced now. Advertising, for example, is very definitely a form of propaganda in which a group of people is persuaded by one means or another to take action in accord with the wishes of another group. Tariffs are a means of incentive manipulation. The point is that we are not in a position to choose one or the other as alternate courses of action. Rather, we must question in what ways we wish the influence of these strategies to operate.

5) Perhaps a useful way of looking at our culture today is to consider that we are presently in a position to effect self-conscious evolution. Our capabilities for storing and relating knowledge are great enough that we can now understand many of the systems of interconnection with which we have only been able to struggle myopically before. Thus, our view of the city should be ecological in the sense that it recognizes that the city evolved in the way it did because of the logic of its symbiotic relationships. The only way we can effect beneficial changes in such a system is to alter the fundamental ecological relationships in a beneficial way. That is a task for responsible engineers.

6) To understand the current economic system one must look not only at the way it changes and responds, but at the way it stays the way it is (its inertia). As Madden points out, "Mental telepathy is unlikely to be vigorously researched by corporations with heavy investments in communications equipment."[1] To pursue this argument, very large corporations and monopolies lack the stimulus of competition, and small companies lack the finances for extensive technical research and development. Perhaps, then, in terms of the strategy which looks to institutional incentives, we should alter the antitrust laws to allow for and to stimulate technical research and development.

7) It would appear that Mao Tse Tung has been able to use propaganda so effectively that he has been able to alter fundamentally the ethical outlook of the individuals of his country. The Communist Chinese people seem to act on the basis of a commitment to the value of collective good rather than of individual gain. Is such a change good? How will it affect the individual creativity and idiosyncrasy?

[1] H. A. Cairns, Ed., *Clash of Cultures.* New York: Praeger, 1965, p. 41.

On the Social Psychology of Organizational Resistances to Long-Range Social Planning

DONALD N. MICHAEL

Abstract—This paper is a brief report and reflection on a three-year study of the social-psychological problems involved in changing public organizations so that they are able to perform social, particularly urban, long-range planning. It reviews the philosophy of the study, the present state of long-range planning, planned-change literature and its implications, and some issues in organizational transformation.

THIS PAPER is a brief report and reflection on a three-year study of the social-psychological problems involved in changing over public organizations so that they are able to perform social long-range planning.[1] Posing and seeking national goals, indeed constructive and positive social survival, appear to make long-range planning mandatory. Yet, our study of organizational resistances to long-range social planning suggests that if present organizational structures and the norms that sustain them are not radically changed these resistances cannot be overcome using available organizational theory or available planned change practice expertise. The conceptual and operational crisis implied in these findings present a major intellectual and professional challenge.

The criteria offered by M. Webber present an excellent conceptualization of the long-range planning technology.

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[1] The time period implied in the phrase "long-range social planning" would vary, of course, with the activity being evolved but, generally speaking, it refers to a ten to twenty year perspective.

They have been used in our study as the reference against which to assess the nature and extent of organizational resistance to long-range planning:

1) Analysis leading to goals setting in conjunction with 2).

2) Forecasts of future setting (differentiating exogenous and endogenous factors) for which the working out of the plan over time is relevant and desirable.

3) Evaluation of alternative plans.

4) Tracing out the consequences for plan of pertinent circumstances outside the plan's direct operating environment.

5) Laying out sequenced chains of actions that define the plan.

6) Evaluation of how the plan is working out on the basis of environmental feedback that permits recycling of the preceding steps.

Of central importance for the social-psychological issues involved are three factors:

1) The requirement that present actions be deeply influenced by estimates of relevant future societal contexts.

2) The requirement that, at all stages of moving from present actions into the future, the environment be scanned and the feedback from it be controlling in the unfolding of the future-oriented movement of the plan.

3) The requirement that goals and the implementation of programs to realize them are intertwined conceptually and operationally. Goals are process guides rather than rigid end points.

In other words, the cybernetic concept of the relation of the organization to its environment must be reflected in the operations of the organization that derive from its long-range planning activity.

At this point the reader may feel this study is beating a dead horse since the Lindblom school of organizational interpretation has already demonstrated that organizations have good logical and operational reasons to respond to their environment incrementally. And they argue that that is the way things ought to be in a democracy. There is no question that this is the way organizations do respond, but as numerous observers have pointed out, this is a major reason why the plight of the society is increasingly desperate. I shall not make the case here since it seems obvious enough on the face of it and I have made it elsewhere [1], that national goals of environmental revival and protection, Third-World development, new city building, educational policy implementation, arms control, technological assessment, biotechnology and social technology all require, if there is to be effective allocation of intellectual and material resources, something radically different from policy formulations based on reflexive mini-twitches in agencies of governance and resource allocation, policy learned in past experiences. We must get ahead of problems and opportunities or we shall be buried under them: entropy increases faster than increments of allocations.

Furthermore, the Lindblomian mode of description does not enlighten with regard to the relationships of organizational structure to the characteristics of the external task environment as these affect and are affected by psych logically-based responses to environmental uncertainty a organizational innovation. These relationships becor critical when organizational response, particularly poli formulation, must be made to problematic futures rath than to a stable past. That is, if we wish to try to redesi organizations to be long range in their activities, we w need to know more about organizational structure and h man behavior in relation to the future-infused environme in which they operate than is provided by convention political-administration levels of description and analysi This study focuses on the level of analysis and descriptio that is appropriate for thinking in terms of the feasibili of changing the people in, and structure of, organizatio so that they can cope with the internal innovations neede to cope, in turn, with their environment, over the lon range, through planning procedures.

That the ideologically dead, or at least dying, horse migh instead be the incremental philosophy itself is strongl suggested by the imagery and rhetoric that increasingly i heard these days avowing the need for, indeed, the fact o long-range planning. It is expressed by the federal govern mental publicizing its efforts to apply planning, program ming, and budgeting (PPB) by congressional efforts to pas legislation relevant for long-range technological assessmen and manpower development, by executive training program aimed at teaching corporate chiefs how to introduce long-range planning into their organizations, by a growin normative literature on social planning, by publication such as *Fortune* and the *Harvard Business Review* with their emphasis on the new management-planning techniques, and by the growth of futurist studies and publications, and by this Workshop.

However, while the rhetoric and the imputation that long-range planning is underway or imminent are increasing, according to our studies little if anything is actually going on that meets the Webber criteria. I will return to this later. This state of affairs is compatible with the body of theory and field study—and I will return to these too—that describe organizational "dynamic resistance" to innovation, to use Schon's phrase [2].

THE PHILOSOPHY OF THE STUDY

Before reviewing more specifically what we have found, let me describe the philosophy of the study. The value premise in this study is that long-range planning is both necessary and dangerous to the democratic ethos. As such, there is need to introduce and implement it with all the sophistication and humanity possible. Hence we had better try to anticipate and influence what may happen in this area in the light of what we know about men and organizations on the one hand, and what we believe about the proper conduct of planning on the other. We have tried in thi study to understand the reasons for, and implications of, this dynamic resistance to innovation about long-range planning in public organizations, in spite of the growing lip service favoring it. Our understanding derives chiefly from a comparison of the normative literature on what planning should be with the literature on organizational behavior and planned organizational change. We have tried to check our literature-based conjectures and to enrich them by looking at what is happening to long-range planning in the real world today. And we have tried to better understand the implications of these processes for public organizations by also looking at the condition of long-range planning in private corporations.[2]

This study represents a preliminary effort at systematic analysis and conceptualization to uncover areas and rationales for specific research and to propose, when feasible, hypotheses for research on the social-psychological problems and opportunities involved in *changing over* to long-range planning in organizations concerned with the public interest. This means, most importantly, government agencies, but it also includes private, public-service, social welfare organizations. Thus the project should be thought of as an expedition, an exploration into an unexamined area of organizational-environmental-interpersonal processes.

The study is not exhaustive. It contains no statistical tables, random samples, or tests of significance. We read and interviewed both primary and secondary sources. In this way, we acquired a sense of the current status of planning activities and the implications for the future by comparing the normative literature about planning and the material on the theory and practice of organizational behavior and change. Illuminated in this way, more specific areas of research and knowledge application can be delineated for further systematic work.

Present State of Long-Range Planning

I will turn first to what we have found to be the present state of long-range planning. We looked some at corporations to see if within that potentially more amenable organizational and environmental setting such long-range planning as defined herein was occurring. Contrary to popular imagery, this is not the case in most corporations. To be sure, the aerospace industry projects hardware requirements a decade or more ahead and organizes its research and development and sales promotions accordingly. Sometimes—but only sometimes—technological goals change as the anticipated environment changes. The utilities organizations and wood grower industries have simply extrapolated demand and planned accordingly. But these kinds of corporations respond to profoundly different characteristics of the societal environment from those which characterize most corporations and all of the public sector. Depending on their particular product, they deal with or thought they dealt with stable environments and highly specialized clientele, and they had no problems of distributive equity to struggle with.

In more conventional corporations, there seem to be n planning systems in operation of the sort represented by th Webber criteria. Some organizations are trying to organiz to plan products and investments beyond two to four year —which seems to be the usual time period for conventiona long-range planning in corporations when there is an long-range planning at all—but the reorganizational cost so far have been so great in organizational and interpersona readjustments that not much has been put in operation an certainly nothing has been operating long enough to conclude that it has been institutionalized even in particula settings. Although there are very small beginnings within very few organizations of trying to design and implemen longer range planning, there is essentially no planning tha looks to alternative futures for the society in which thes groups hope to operate and then alters present corporat goals and styles to attain or avoid those futures. The usua corporate procedure is to project a future that is compatibl with present values, operating styles, statuses, and commitments and on that basis make their plans to grow in tha projected direction. Indeed, it has been the experience o one of the most conscientious and sophisticated of th organizations doing futurist studies that most organization are so narrow in their perceptions of their relationship t the larger society, and so unfamiliar with the processes o thinking from the future back into the present, that futuris studies are useless to them. Even when corporations clain they want to benefit from such studies for planning purposes they actually use the studies only if the projections ar compatible with their already-held plans and perspectives Taking seriously and acting on a future that jeopardizes present successful allocations of status and rewards is simply too threatening.

Thus even though corporations seem to be the organizational setting in which long-range planning has the most likely opportunity for realization in our society, little if any planning is actually in operation except in certain areas o product planning and capital investment. Here, however narrowness of context and purpose are contrary to the planning perspectives needed in the public sector.

Remember that our attention to the corporate sector was only an alerting procedure to ascertain factors that might be worth comparing with our data from public sector organizations and from the literature. What about the public sector? There is even less effort or success at long-range planning here than in the private sector. There are a very few attempts at goal setting, a few attempts at using planning technology, and a few solicitations of futurist studies. But the goal setting is generally too narrow, the interrelationships are ignored, and they are based on simple projections of present values and conditions. Planning technology has been misused or not used: PPB and data banks are usually ritual activities. At best, they are used to facilitate marginal improvements in present-oriented operational activities. Futurist studies end up "on the shelf"; and no organization has even thought about the requisite feedback system for monitoring and revising planning implementation. Gen-

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[2] invaluable part-time staff contributions to this study have been made by J. Crowfoot, A. Gruskin, and R. Olson. A work group has deliberated intensively for several two-day meetings. Its members are R. Bauer, H. David, M. Dumont, R. Kahn, P. Ratoosh, D. Schon, M. Webber, and A. Westin.

erally speaking, the present so preoccupies agency personnel that the future is left to take care of itself. Often the justification for this attitude is why take risks now to deal with an unknown future. In addition, the exigencies of reelection rationalize avoiding serious attention to the longer range.

A few public interest, private organizations seem to be more genuinely preoccupied with the future but seem equally unable to translate this concern into action. (The only exception we know of is the National YMCA.) That is, they are unable to make the basic shifts away from the priorities and personnel that the present rewards. Meantime, Congress calls for technology assessment, holds hearings on the need for longer views in planning manpower and coping with the urban condition, and proposes legislation to implement the assessment capability. No laws have been passed, but even legislation cannot itself deal with most of the steps in planning.

THE PLANNED CHANGE LITERATURE AND ITS IMPLICATIONS

I turn now to the results of our literature exploration which is the crux of our study. The present "real-life" situation of itself proves nothing; the pressures for long-range planning and the technology to do it are only now developing and the future will be the more critical setting for assessing the possibilities of changing-over organizations. The literature on planning and on organizations is a more fruitful means for estimating the nature of that future. The present would be more important if what is going on were contradicted by what the theory and research, as represented in the literature, would predict. But there is no contradiction. When we compared the normative requirements for long-range planning with what is known and theorized about organizational behavior, the consequences for tomorrow look like the circumstances today.

Of the many ways I could summarize the situation, I choose that of describing some operational design problems and then some organizational transformation problems. These will be categorized to reflect on the tasks Webber designated as defining the long-range planning process.

Uncertainty

Uncertainty is to be differentiated from risk. Risk pertains when one thinks one knows the probabilities involved and makes risky choices based on the probability-based expectation or evaluated hope that things will go one way rather than another. Models of exemplary behavior for rational men and myths about rational behavior assume known probabilities for making decisions. Uncertainty pertains when you know, or suspect, that you don't know what you need to know to make risk-type choices. You may have too much or too little information: either way, one knows one is working in the dark. Friend and Jessop [3] have distinguished three types of uncertainty that operate in planning-type situations:

1) Uncertainties in knowledge regarding the environment relevant to the planning task.

2) Uncertainties regarding the future intentions of those responsible for choices of action in related fields of activity.

3) Uncertainties regarding the appropriate value judgments upon which to make planning choices.

These lead to feelings of need for: 1) more research regarding environmental characteristics; 2) more coordination; and 3) more policy guidance.

None of these needs for uncertainty reduction can be met adequately in the long-range planning situations. However, as Schon and others have shown, rational men find uncertain situations threatening and usually avoid becoming involved in them. Lindblom [4] warns in support of the political and logical reasonableness of incrementalism, "nonincremental policy proposals are typically unpredictable in their consequences." Uncertainty is avoided by ignoring the issues that lead to uncertainty, or by gratuitously translating an uncertain situation into a risk situation. Much of the ritualized rationality that characterizes high strategy in the nuclear age, especially with regard to thinking the unthinkable, typifies these responses. But either is an inadequate response to the problems of long-range planning wherein the very problematic nature of the future means the situation is inherently uncertain. Organizations arranged so that they could deal with uncertainty would be ones in which the members are trusted enough by each other and by their relevant constituencies to propose goals, and means for reaching them, which are original, tentative, and subject to revision as the organization environment moved into that future—a future in part invented by their actions and in part imposed by the actions of others. We find little evidence that men who have become successful by defining themselves to themselves and to others as rational and pragmatic are able to live openly and continuously with uncertainty. We find no evidence that we know how to *design* organizations that can work effectively in an explicit context of uncertainty.

A Turbulent Environment

Emery and Trist [5] have conceived of and examined the concept of the "turbulent environment." This is the task-relevant external environment for an organization. The characteristics are such that much that happens within it that is significant for the organization is not the result of actions taken by the organization. Essentially, it is an uncertain environment full of unanticipatable amplifiers and attenuators. The authors give reasons for arguing that this is the present and anticipated environment for organizations in highly developed, complex, technological societies. If they are right, then internal differentiation of organizations to match their environments will be extremely difficult and never more than temporarily in phase. It also means that feedback from that environment will face the organization with formidable, probably overwhelming, regulatory requirements for adjusting means and ends at the time, much less in an anticipatory manner. Both of these issues will be discussed, and clearly turbulence increases uncertainty with the consequences mentioned above.

Redefinition of Internal and External Functional and Operational Boundaries

Cyberneticists working from their theoretical perspectives, organizational theorists such as Miller, Rice, and Thompson, and planning theorists such as Lawrence and Lorsch all stress that organizations must be differentiated internally to reflect their relevant external environment. Moreover, in order that the overall organizational goals can be pursued, the organization must integrate these differentiated activities. But one thing is clear from both literature and the field: the existing intra- and interorganizational differentiation and integration of agencies "serving" the public interest are appallingly mismatched to that public interest. The new technologies of data banks, social indicators, simulation, etc., could permit greater apposite differentiation and integration than has ever been possible. Futurist studies could help delineate patterns of differentiation and integration that might be more responsive to the developing situation than those derived from the past. But when these technologies, which are all a part of long-range planning technology, are applied for purposes of establishing new differentiations and integrations, they are profoundly threatening to preferred and stable views of: 1) what is important "out there"; 2) internal empires and status; and 3) definitions of self in terms of skills (see what follows) and one's internal and external utility. For these reasons, very few persons will be prepared to give up the rewards of present boundary arrangements in order to try to cope better with a problematic future, or even to become embroiled in problematic redefinition of present operational and functional boundaries.

New Skills

Use of long-range planning technology depends on acquiring new skills in interpreting data, reorganizing personal perspectives, coping with turbulence and error, living with uncertainty, task-oriented interpersonal relationships, sentient relationships, and in future orientations. A crucial psychological usefulness of organizations is the protection they afford their members from being overwhelmed by the environment. But all aspects of long-range planning require those involved to enlarge their skills at coping with greater personal and societal complexity and turmoil. To the extent programs and perspectives will need revision, everybody in the organization must have these skills. However, not everybody in existing organizations can learn, or cares to learn them. From top to bottom, the easier situation is to avoid the challenge and disruption by avoiding long-range planning.

Feedback

The *sine qua non* of long-range planning is the capability to evaluate continuously the relevance of the goals sought and the means used for seeking them and, on that basis, to revise continuously both the goals and means as appropriate [6]. The organization must seek information in the environment and must act on it. However, if the environment is turbulent, its characteristics are not generated exclusively or primarily by its interaction with the specified organization. Thus the feedback is very likely to indicate that things are either going differently than intended or are mystifyingly indeterminate as far as assessing the impact of the organization on the environment from the perspectives of the long-range task with which it is coping. Not only must the organization be structurally differentiated and integrated to deal with such discomforting turbulence and evidences of inadequacy but, to do so effectively would seem to require a profound shift in values. Instead of being a threat to those "responsible," open "error embracing" must become the necessary way to go about societal learning through the revision of on-going plans. Political man and rational man avoid error acknowledgment like sin—which, indeed, it smacks of in our society. In the existing way of doing things, a rational and skilled man has, by definition, the good judgment to choose his risks correctly. In terms of conventional wisdom, he does his very best to avoid getting mixed up with uncertain situations. But in the open-system cybernetic philosophy treats error as a natural property of such systems to be detected *after the act* rather than to be anticipated. Indeed, the capacity to adjust depends on effective use of error. But we do not now have an error-embracing ethos, nor do we know how to design organizations that have a capability for continuing redifferentiation and reintegration as a function of what the feedback from the environment requires.

Technological Inadequacy

Since concepts and data for selecting among them are relatively primitive as regards our understanding of the societal processes that would be the subject of social long-range planning, it follows that our computer-based simulations, data bank content, social indicator selection and interpretation methods, and methodologies for futures conjecturing are also primitive. As a result, potential users feel justified in rejecting long-range planning on these grounds alone, whatever else motivates them. But this means that the incentives, resources, and opportunities needed to improve the technology by evolving it in its natural setting, in the library, or in the laboratory are comparatively few. This situation constitutes a self-fulfilling prophecy for those in public organizations who say long-range planning will not work. (As I have said elsewhere, I do not think long-range planning would work well under the best of operational circumstances for a long time to come. But this way, it will not work at all!)

In sum, organizations that should apply long-range planning technology and philosophy in public interest areas to enable anticipated future states to guide present actions must live with the personal and organizational threats inherent in: acting in uncertainty; acquiring new skills; living with frequent boundary redifferentiations and reintegrations that would upset present statuses and senses of self; and embracing the errors that inevitably will be produced in part by the planning technology itself and in part by the feedback from a turbulent environment. These problems and processes would repeat themselves endlessly.

I have outlined the requirements to be met *within* one organization, and have not discussed here the obvious problems of inter-organizational collusion and competition and the effects of these on the above delineated internal requirements. It is no wonder long-range planning is so thoroughly resisted!

Now that I have speculated about some of the social–psychological sources of organizational resistance to long-range planning, let me describe some of the social-psychological issues of organizational transformation.

ISSUES OF ORGANIZATIONAL TRANSFORMATION

It follows from the above discussion that a necessary precondition for long-range planning is organizational development. The personal and interpersonal skills and flexibilities needed to cope with the emotional and intellectual burdens of the change-over and the operating situation far exceed those that most people seem to possess, and certainly exceed those that organizations, particularly public agencies, reward. But these strengths and skills would also need to be linked to the appropriate structure of individual, task group, and functional arrangements. Finally, both people and structure would have to be matched to long-range planning technology *per se*. And all of these designs would have to be appropriate to the relevant environment. But not, of course, in a once-and-for-all sense since the environment and the technology, hence the people and the structure, would be changing.

Our review of the literature on organizational development techniques makes it clear that none of the current techniques available 1) to shift interpersonal skills and personal behavior, 2) to recommend some valuable structural changes, or 3) to better relate some organizational tasks to through-put technologies, is adequate to the challenge posed here. What is more, there is *no* theory or technique that combines technological, interpersonal, and structural organizational change.

In the public sector, the situation is still more discouraging. Experience and theory make clear that organizational development takes years of deliberate effort. This time period must be dominated by a champion at the top of the organization with sufficient control of resources and organizational boundaries to make possible the controlled sequencing of the organizational change procedures. None of these requirements is met in government. Of special importance, no one high in government organization can have sufficient control of organizational boundaries for a long enough period. There are congressional and client constituencies available to those inside the organization that make the boundaries highly permeable and boundary control impossible. And these problems and limitations are common knowledge, which further reduces the incentives to put real effort into organizational change.

It looks like 1) we do not know how to design organizations to do public sector long-range planning and 2) even if we did know how to design them, we do not know how to deliberately get them transformed from what they are into the appropriate new forms. What then? One could hope that we will stay ahead of entropy. I believe this is a tragically naive hope. One can "cop-out" in all the approved ways a rich multiple-option society provides. One can seek revolution, but I have yet to see a model of a complex society that overcomes the theoretical and practical problems posed here which apparently have no ideological limitations. One can look for surrogates for long-range planning and for the organizational development processes that provide its functional equivalents. That is what we are now looking into. Let me mention some directions of our work.

Crises and disaster appear to be the occasions affording the greatest opportunities for basic structural and personal changes in organizations. Social and ecological crises and disasters are inevitable, probably in increasing numbers. What about contingency planning of programs that includes designing organizational changes to be instituted in fluid, crises situations? The problem here, aside from our pathetic design capability limitations, is that contingency planning of this sort on a sufficient scale to matter probably depends on acknowledging publically *before the fact* that one has no real capacity for avoiding the crises. Otherwise, the planning effort will be too feeble. The needed skills are scarce and hard to recruit. But acknowledging impotency has obvious problems for the agencies (or foundations or private social service organizations) that would take this step. What's more, the contingency plans, by the very fact that they are too disruptive of conventional rewards to be instituted under every-day circumstances, will be politically controversial and, thereby, vociferously rejected in conventional political quarters.

There is one hopeful (?) social-psychological factor that may operate here: As the calamities increase, it may be easier for leaders to acknowledge error and incompetence simply because many of them will be perceived as transparently incompetent. In that way, the whole error-embracing learning philosophy regarding long-range planning might be more implementable, because it will be obvious we simply do not know what works. But the more typical psychological response in crises is to seek leaders who comfort by insisting they have *the* answer.

Another approach is to see whether the planning process can be "partialed-out" to other parts of the society that are functionally better able to accomplish them. For example, corporations or think-tanks could do the radical imagining. Advocates and citizen groups could do their own scanning of the environment and force the feedback on the responsible agencies. Laws could act as regulators, in Vickers' sense, sensitizing the system to when it is going in the right direction [7]. But the structures that would accomplish this in the public interest do not now exist *even in theory*, much less in a necessary interpersonal reward system within the organizational and inter-organizational matrix.

There is, in principle, another way to view these problems and that is to try to discover a theory that makes possible the needed organizational design and its implementation which would encourage and permit long-range planning. Throughout this study, I have been haunted by a piece of engineering history: There was a time when aerodynamists could design pretty good airplanes but the theories upon which the designs were based also said the honeybee could not fly. Today, they design better planes and can also demonstrate how the honeybee flies. Maybe society, and the organizations that comprise it, can be made to fly by different or additional principles than those we have discovered so far.

To my mind, the most promising approach here is to think about the possibility and feasibility of a complex society where organizational structures and the norms that legitimate them are designed to reward a different set of assumptions about the nature of man. It seems clear that it would have to be a definition that says it is natural for man to embrace error, live in uncertainty, live *in* nature, be trusting, and be as constructively and openly feelingful as he is now constructively rational. "Unnatural" as that definition of human nature seems to us, it is age old—Huxley has called it the *Perennial Philosophy*—and seems to be making sense today to a growing number of people (I think). Whether the occasional, tentatively successful, experiments that have matched "human nature" and organizational structure in this perspective can become the norm or even become an important strand in the dialectic of societal change remains to be seen. But if our theory of man and his organizations cannot be replaced or radically revised, we are in terrible trouble. For national goals will depend on long-range planning for their realization and national goals as planning guides will be a necessary input to the planning process. The way things are, that process is inaccessible to us.

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A Framework for Science and Technology Policy

HARVEY BROOKS

Abstract—**Science by itself has no impact on society. Its impact is mediated through the professions, all of which are concerned with design in some sense. Science and technology are both option-generating processes, and the options have a high mortality. It is only the application of technology in a replicative process that is option-choosing and commits us to its social consequences.**

Social systems do not conform to traditional systems analysis. They do not have single objective functions. They exhibit conflicting and internally inconsistent goals. Systems analysis which aims to incorporate society as part of the system must incorporate these conflicts and inconsistencies as part of the analysis.

Paretian environmental analysis and Allison's models of governmental decision-making are described as illustrating how the concepts of systems analysis might be broadened to take into account the response of social groups and bureaucratic structures to technocratic plans.

If engineers are to bring systems thinking to bear on social problems, they must learn how to incorporate social and political theory into their analytical framework ab initio.

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Science, Technology, and the Application of Technology

THE RECENT popularity of such terms as "science policy" or "science and society" has led to a good deal of confusion in thinking about the relationships between science, technology, and society and the responsibilities of scientists and engineers and other technologists in these relationships. The term "impact of science on society" is an extreme shorthand expression for a process which is very complex and involves many elements besides science. By itself science has no impact except on man's thinking and the way he views himself in relation to the universe. Science is not action but thought, and thought which aspires

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Goals for Technology

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Abstract—If modern technology is to impact successfully on a significant social problem, the quantitative model must lead to a finite set of alternatives, each clearly referenced to its social, economic, and political constraints. From such alternatives, priorities must be established by the political process—it is at this step that the major current impediment to progress occurs. The engineering community carries the responsibility of elucidating the specific decisions which the public must make.

THE SCIENCE advisory system of the Federal Government involves thousands of engineers and scientists attempting to impact the system in a variety of ways—from peer reviewing of proposals to service on standing committees and ad hoc commissions and from personal contacts with members of the legislative branch to overt attempts to influence public opinion. A primary objective of this complex advisory mechanism is to establish specific national goals which represent realizations of the positive contributions technology can make to the improvement of the quality of life in this country.

In recent years, there have been a number of attempts to evaluate this advisory mechanism. Articles in *Science*, reports by Nader's organization, studies by elements of the system (the President's Science Advisory Committee and the Academies), and the growing body of literature on science–government interaction have cited a number of successes (for example, in biomedical research or environmental activity) and certain marked failures (most notably, in the current public attitudes toward technology, but also in such areas as our inability to reduce the annual automobile fatality rate, to curb the drug epidemic, and to ameliorate the serious urban problems).

Indeed, if one looks at the variety of national programs of the past decade which have been developed to attack major social problems, one is tempted to draw the conclusion that the only positive result is the demonstration that each of these will not work. In the area of education, for example: we seem no nearer to a resolution of de facto segregation problems; educational television has been rejected in formal education as a means to obtain improved system performance within cost constraints; computer assisted instruction is considered still a decade or more off by a company which has led in the investment of dollars and creative manpower; the Head Start program is widely criticized; and the Department of Health Education and Welfare has quietly dropped the ES '70's program and less quietly proclaimed performance contracting a failure. One has the impression that every three weeks the *New York Times* announces in a front-page story the fantastic success of a new method for teaching reading, with another lead article faithfully following a week later to announce that test results were manipulated in that particular program.

We seem to be left with only a few new and untested programs: day care centers for pre-schoolers and open universities for post-schoolers. With such exceptions, we are in a state of idea bankruptcy, not only in education, but also with respect to most social problem areas. The paucity of exciting novel approaches coincides with the national recognition that these problems are not as trivial as the technological challenges of developing a new weapon system or placing a man on the moon.

We could go on to chronicle the many confluent forces which lead to the current national attitude toward technology which threatens to force legislation limiting, directly or indirectly, the development of that new technology which is so essential if we are to ameliorate these problems. This is the same national attitude which results in a one-year drop in freshman engineering enrollment from 71 000 to 58 000, and which marshalls public opposition to new technology without any willingness to understand the alternatives.

All of us in technology, however, are far too aware of the difficulties and hostilities we face. It is precisely at such a time that we must forge new, creative, and positive programs. The very fact of the wide perception of the failure of past efforts is, in one sense, the greatest cause for optimism about the future. Not only will any small success represent a refreshing change, but after several years of naive optimism, we now recognize the enormity of the problems, we understand the necessity to make progress by small steps, and we appreciate the complex interaction of social, political, and economic factors with technology. We have laid the groundwork for major technological contributions to education, health, environmental control, transportation, housing, and the like. We are emerging from the difficult conversion from the military–space economy to the civilian economy.

THE BASIS OF A PROGRAM

A specific program designed to apply technology to improve the quality of life by effecting change in any particular aspect of that life (education, transportation, etc.) must be based upon an adequate quantitative model of the problem area. If we are discussing a specific service function, the model must encompass not only the costs of the service, but also definitive measures of the quality—or the ways in which there is a deficiency.

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This quantitative model, coupled with an understanding of the modern technology as well as the existing social and political constraints, allows logical decisions on the details of the program. Typically, a long list of possibilities is generated as possible avenues of attack. Social scientific information is then required before priorities can be established within this list—information not only on the impact on all aspects of the social system, but also on human attitudes toward change. When priorities are established, the program then entails technological development paralleled by educational and social programs preparing for the innovation.

In order to illustrate these general ideas, we turn to a particular example: health care. An intensive series of national reports dating well back into the Johnson Administration has documented the relatively poor health status of Americans compared to people in the other advanced nations of the world. (Admittedly, such quantification has to be interpreted with care, since there really are no measures of the average quality of health; instead mortality and serious-disease rates are used.) Furthermore, the many national studies both within and without the Government seem to agree on a number of causes—several ways in which the U.S. health services system is not meeting desired performance levels in spite of the high and rapidly rising cost of health care in this country.

The interesting feature of this list of causes is that in many cases technology can make a definite contribution if the means is found to implement a technology-development program by providing the necessary federal impetus, aggregating a market enough to make the field attractive to industry, and establishing appropriate guidelines and standards.

Even a cursory glance at the causes affirms this potential rule for technology.

1) Senior Citizens: Here the sorry state of nursing homes has been emphasized by President Nixon during his Nashua, N.H., trip and in "popular" terms in the book *Where They Go to Die*, as well as in a series of television specials and articles in the press. The lack of technological development is apparent to any visitor to such homes, where there is essentially nothing to improve the mobility of the physically handicapped, to assist individuals who are unable to care for themselves, or to utilize computer video terminals to provide entertainment. Merely a typewriter designed especially for users who are unable to direct their fingers to a small area would be a significant aid, as Myron Tribus' Dartmouth College students showed in their work with spastic children, and some of these patients could be given a strong purpose by using technology to allow them to prepare materials for blind people. As a final example, there seems little justification for a cost of $1000 for a device to hoist a human being one flight of stairs in his home a few times a day.

2) Middle-Aged: One of the principal reasons for the poor U.S. life expectancy is the relatively high mortality rate of citizens of 25–45. While the causes are not completely clear, certainly hypertension and alcoholism are significant factors. Even more surprising is the high rate of physical disability, with the number of handicapped growing markedly faster than the output of rehabilitation programs. In spite of the publicity associated with the "Boston arm" and elaborate reading machines for the blind, the percentage of physically handicapped who benefit significantly from modern technology is exceedingly small.

With less than 20 percent of the blind reading braille, the need for a national program to capitalize on the low-cost audio cassettes is apparent. Laser canes as mobility aids have been heralded, but the vast majority of the blind experience great difficulty in moving around urban areas. Indeed, until very recently our industrial process did not even make available a folding cane—certainly not particularly high technology.

3) Young Adults: The 15-percent drop since 1900 in the ratio of females to males in this country has received wide publicity because of the implications for women's liberation and the relationship to the optimum marriage age for males and females. One of the important causes of the drop is the death rate among young male adults: deaths resulting from automobile accidents, homicide, suicide, and drug addiction.

Technology can play a significant role in mitigating this situation. In the drug-epidemic problem, for example, system analysis is desperately needed to determine at which points intrusion into the manufacture, distribution, and use network is likely to have a meaningful effect. For instance, the administration has publicized the agreements with Turkey to limit the poppy crop grown there, and on Long Island restaurants are boycotting French wines until France takes strong action to close the Marseilles manufacturing plants. Serious proposals have been made to use satellite observation to monitor the location of poppy growth throughout the world.

Yet none of these measures really seems significant in terms of the U.S. problem (although perhaps they can be justified on world-wide humanitarian grounds). With drug prices in the U.S. markedly higher than elsewhere in the world, this country represents the prime market. It appears that more than 95 percent of the world's poppy crop would have to be eradicated before we could anticipate a major change in the supply in this country.

In the problem of automobile safety, technology can play several immediate roles beyond the obvious improvement of vehicles and highways. The air bag, now dictated for installation in all cars by 1975, requires major technological development, as emphasized in last month's RECAT report by the Office of Science and Technology.

As the President's 1972 State of the Union message and the March 16 special message on science and technology both emphasized, a major effort is needed in the development of emergency medical care systems and devices to reduce the third of the 55 000 annual auto fatalities which are attributed to improper emergency care. The 88-percent expansion in Federal funding proposed for fiscal year '73 for new demonstration projects arises to "pull together the technologies into a system which effectively links com-

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munication, transportation of victims, ambulance equipment and service, trained manpower, and emergency room hospital service."

Breadth of a Program

The three aspects just mentioned represent, of course, only a very small part of the model for the present U.S. health care system—the model which shows as vividly the many specific points at which existing technology could be used to modify the overall quality of health care. We have not discussed at all the health problems of children, the soaring costs of care for the critically ill, or the most pressing problem of the more than one-third of our population which is effectively separated from the health care system except in situations of dire emergency. (In this last direction lie perhaps the major challenge and opportunity for instrumentation technology, and one of many chances to demonstrate that technology can indeed enhance individuality.)

From such a model (developed naturally in very much more detail than is possible in these brief notes), we can formulate a lengthy list of alternatives—specific governmental or national programs which effect a positive change in the health status of this country within the existing social, political, and economic constraints. Such a list would certainly include, for example, the following:

a) the design of an array of ambulances and emergency vehicles similar to that now in existence in the Soviet Union and ranging from general purpose to highly specialized;
b) the development of low-cost special-purpose minicomputers for hospital information systems;
c) the realization of a greatly expanded nationwide network of artificial-kidney centers to treat the 30 000 patients annually who are now unable to obtain help;
d) research directed toward malnutrition tests which can be administered early and at low cost to large numbers of people, particularly expectant mothers, where nutritional deficiencies seem to adversely affect the child.

Just these four possibilities point out the wide range of technological difficulties which can be anticipated for the complete list of alternatives. The programs a) and b) are straightforward from a technical standpoint—they require no new technology. Indeed, a) merely awaits some assurance of a suitable market. Program b) requires at least a modest study of the true needs of this aspect of the health care system, or perhaps even more, an agreement among hospital administrators and managers.

Item c) begins to introduce technological difficulties, or at least uncertainties, because of on-going research directed toward cost reduction, simplification, and portability of artificial kidney machines. Finally, the nutritional-test program demands a significant research effort and hence involves more uncertainty as to success.

In each of the hundred or so possible programs which can be listed for improving health care by technology, the description of the program must also include the model for the social and economic constraints within which the new technology must operate. For example, the ambulance-redesign effort (studied recently by both HEW and the National Academy of Engineering) is severely limited by the confusing multiplicity of responsibilities for ambulance operation in the typical city, the stringent financial constraints under which both municipal and entrepreneurial systems operate, the inadequate training programs for ambulance personnel, and a disarray of Local and State statutes governing operation. (The proposed Federal program mentioned earlier will attempt to find, as pilot projects, a small number of localities where this confusion is minimal, in the hope of inducing other cities and local governments to take positive steps to create the legal and social setting amenable to the introduction of modern technology).

Limitations of Technology

Thus we are now at the point where a list of alternatives has been generated, each complete with the social, political, and economic portions of the model and the program plan. Indeed, each can be evaluated on a quantitative basis if we with to strengthen the argument by demonstrating that a proposed program will yield an equivalent dollar benefit greater than the cost. (Reading various cost/benefit analyses prepared to substantiate proposals, one rapidly gains the impression that the nation could easily utilize its entire tax revenue in new programs which would reap benefits far exceeding costs.)

The actual implementation of any subset of these programs requires a decision on priorities. It is at this point that the political process rightfully assumes the decision-making responsibility. Unfortunately, the political process is often not assisted very effectively by the scientific community. Anyone who has sat on biomedical advisory committees with a variety of physicians is acutely aware of the inability of the medical experts to agree on priorities. Quite naturally, each tends to feel that an additional $100 million of federal funding for health should be devoted largely to his own field of specialization. Every administrator of an existing program is acutely aware of his own funding limitations and argues for expansion of his program in preference to initiation of a novel effort. The politicians have to be sensitive to public concerns and have to emphasize programs which involve the direct flow of money to critical communities or which have a high degree of visibility (such as the artificial heart program or the cure-for-cancer undertaking). Finally, hearings before Congressional committees tend to encompass extreme viewpoints rather than studied evaluations by relatively disinterested experts.

In the midst of all these divergent forces, establishing priorities in a quasi-logical fashion requires exceptional leadership and an exceedingly strong science advisory mechanism—a mechanism which does not hesitate to enter the political arena in order to win support for desirable programs. The professional or scientific society which insists on maintaining assiduously its detachment from the political scene (often under the excuse of retaining its favored status with the Internal Revenue Service) abdicates completely its responsibility to represent its members in placing before the public an accurate picture of the technological features of major issues and to ensure appropriate scientific input to the establishment of national priorities.

CONCLUDING COMMENT

Most of today's serious social problems can only be ameliorated by the intelligent use of technology. Technology cannot change the urban or social environment and human behavior: it cannot solve major social problems such as unequal education or health care; it cannot solve the problems of increasing productivity in the service sector (which now employs the majority of our workers) and at the same time decreasing unemployment; it cannot yield an appropriate international trade balance regardless of diplomatic and international economic developments.

But in each of these aspects, the human and social use of technology can lead to marked improvements in our quality of life. The technology exists. The needs are widely recognized. We are primarily stymied by our inability to develop workable procedures to establish national priorities at a time when so many competitive forces are acting on the political decision-makers that it is increasingly difficult to focus efforts or resources above critical size on any specific program. Into this gap, the technology profession must move with the individual engineer, the professional society, the special advisory and evaluative committees, and the major national resources such as the National Bureau of Standards and the National Laboratories.

Toward a Framework for National Goals and Policy Research: Notes on Social Indicators

F. KARL WILLENBROCK, FELLOW, IEEE

Abstract—Quantitative information and factual indicators are essential for informed decision-making, and science and technology policy-making is no exception. However, there are no social indicators as there are economic indicators. Direct measures which relate to technological accomplishments are almost impossible to obtain. Analogies and anecdotes are the arguments used for programs proposed in problem areas rather than specific measures or specific indicators which permit the evaluation of the effectiveness of the program.

In addition to the lack of quantitative data, there are economic and institutional practices and regulations on an international, or state and local level that often act as powerful nontechnical barriers to technological enhancement and change. These include state highway regulations, state building codes, tax rates and structures, the patent system, restrictive application of anti-trust and trade regulation, absence of and inadequacy of nonperformance based standards, and subsidies and tariffs.

The methods of scientific investigation and the social engineering called systems analysis which have been primarily successful in the solution of military and space problems have important roles to play in this area. They can provide the framework for the determination of the particular types of qualitative information needed to measure the nation's social health.

INTRODUCTION

QUANTITATIVE information and factual indicators, in general, are obviously essential for informed decision-making, and science and technology policy-making is no exception. We are by now so accustomed to seeing and using economic indicators, such as gross national product, price indices, and national income accounts, that economic policies would hardly be considered without reference to a wide variety of these indicators. Social policies and policies related to science and technology, in comparison, do not have similar indicators. Although it may appear as though comprehensive economic indicators have always been available on a routine basis, they actually were developed in the 'thirties, and then were not developed overnight. There is a long history of research and development by economists and econometricians because progress required theoretical developments and was not just a matter of collecting data. It appears, therefore, that there is a long way to go before quantitative support for science and technology policies can attain the sophistication and scope available in the area of economics. No attempt will be made here to lay out the necessary theories for science and technology indicators. What we shall do first is to discuss the need for quantitative information.

Quantitative information for rational decision-making is essential because it enters into nearly all aspects of the process of arriving at good choices. One type of quantitative information can serve to identify problem areas. The greater the detail in the information, the sharper can be the focus in terms of providing an understanding of the problem and the nature of the action that might be needed. For example,

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Unified Program Planning

J. DOUGLAS HILL, MEMBER, IEEE AND JOHN N. WARFIELD, SENIOR MEMBER, IEEE

Abstract—Program planning begins with problem definition and ends with planning for action. The key products that result from the problem definition, value system design, and system synthesis steps are discussed and interrelated through the use of interaction matrices. Particular emphasis is given to defining objectives and to defining a set of measures on the objectives by which to determine their attainment. Interaction matrices relate objectives measures to objectives and link activities and measures of their accomplishment to the attainment of objectives. A major consequence of program planning is the choice of a program to pursue, and identification of the projects that will be carried out as a part of a selected program. Selecting the set of projects is discussed in terms of consistency with corporate or agency policy, and the economics, risk, and potential benefits associated with each project. A criterion function that incorporates the latter three factors is described and proposed as a practical way of evaluating the relative merits of projects.

INTRODUCTION

DEVELOPMENT of a theory of systems engineering that will be broadly accepted is much to be desired. The process of developing such a theory is iterative between *form* and *content*. If one has a form, i.e., a broad framework for such a theory, the content can be matched to that form. In the process of developing the content, it may be found that the form is deficient and requires change. Then the content will have to be reorganized, amended, and augmented. This may result in further modification of the form.

Two things can be said about the initially chosen form, with which the content is to be associated:

1) The form does not have to be totally correct, but only reasonably adequate to permit the content to be developed and structured.

2) Without such a form, the iterative process needed to develop the theory cannot proceed.

An initial form that seems quite adequate for development is that given by Hall [1]. This form is a three-dimensional morphological box. Two dimensions of this box are the *phases* and the *steps* of systems engineering. If one takes these phases and steps as given for beginning the iterative development of a theory of systems engineering, a significant conceptual obstacle to the development is overcome. It then becomes possible to proceed to relate existing content to the phases and the steps, and to discover where there is a need for new ideas to augment that content.

Fig. 1 shows Hall's matrix with seven phases, the seven logic steps shown as coordinate indexes. The a entered in this matrix represent sets of activities associated with each square of the matrix. For example, a_{11} represents those activities to be carried out in the problem definition step of the program planning phase. This paper seeks to develop content associated with phase 1 of Hall's matrix, the program planning phase.

In presenting the framework, Hall did not attempt to spell out the content in any detail, but he did call attention to the use of the framework as an "aid to discovering, or seeing more clearly, unique activities." It is in this sense that the program planning phase described in his paper is used. It is important to read his paper before proceeding with this one.

It is intended in this paper to discuss steps in the program planning phase as a connected set. It is hoped to show that while there is continual iteration and reevaluation among steps in this phase, it is possible to unify the process of program planning. This is done by linking the primary products of various steps in a way that allows documentation and display of an overview of what has transpired. Though this paper is limited to the program planning phase, much of what is presented could be applied to other phases as well.

Because of the complexity, and the need to be able to perceive a multiplicity of relations, a graphic approach seems essential. An example will show application to planning for the development of short-takeoff and landing (STOL) aircraft as part of an air-transportation system.

PROBLEM DEFINITION LINKAGES

At the outset of a program-planning activity, an organization is faced with defining a problem or issue that the organization might wish, after suitable study, to address. The assumed input conditions are a broadly defined set of organizational goals and a set of available resources. Problem definition is usually a group activity since it requires an *outscoping* in thinking to encompass a broad scope of potential ideas and candidate problems. Outscoping is a deliberate group attempt to embed the problem or issue in the next larger problem or issue iteratively in order to expand the scope until the problem or issue is seen in an encompassing context. This requires a language in which to develop and portray the product of the group. The language of graphics appears to fulfill this need. Trees and matrices can be used to provide a unifying visual picture of the program plan as it evolves.

Problem definition in the program planning phase is needed for the value-system design step and the planning for action step. It is also needed for the problem definition steps of later phases. Twelve products of problem definition are:

1) a well-conceived title for the problem or issue;
2) a descriptive scenario, explaining the nature of the problem, and how it came to be a problem, presenting as much history and data as can be prepared with available resources;
3) an understanding of what disciplines or professions are relevant to an attack on the problem;

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Phases of the Coarse Structure (time ↓) \ Steps of the Fine Structure (logic →)		1 Problem Definition	2 Value System Design (develop objectives and criterion)	3 System Synthesis (collect and invent alternatives)	4 Systems Analysis (deduce consequences of alternatives)	5 Optimization of each Alternative (iteration of Steps 1-4 plus modeling)	6 Decision Making (Application of Value System)	7 Planning for Action (to implement next phase)
1	Program Planning	* 11	* 12				* 16	* 17
2	Project Planning (and preliminary design)	* 21						
3	System Development (implement project plan							* 37
4	Production (or construction)				* 44			
5	Distribution (and phase in)							
6	Operations (or consumption)	* 61						
7	Retirement (and phase out)	* 71	* 72				* 76	* 77

Fig. 1. Hall activity matrix.

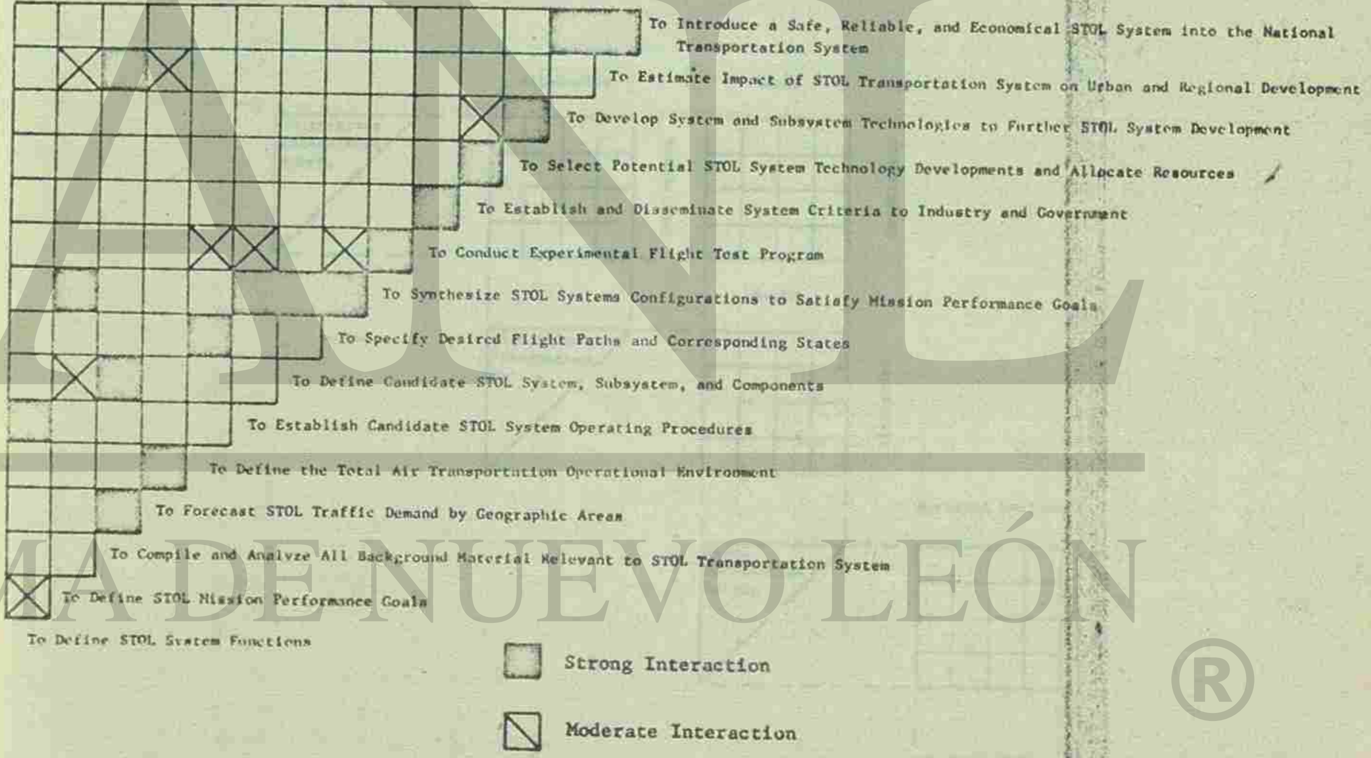


Fig. 2. Example of self-interaction matrix.

4) an assessment of scope;
5) a determination of the societal sectors involved;
6) an identification of the actors to be involved in the problem-solving situation;
7) an identification of need;
8) an identification of alterables (those elements in the system that are subject to change);
9) an identification of major constraints;
10) some partitioning of the problem into relevant elements;
11) some isolation of the subjective elements of the problem;
12) description of interactions among relevant elements of the problem.

It is particularly important during the problem definition step to congeal the ideas of the planning-group members.

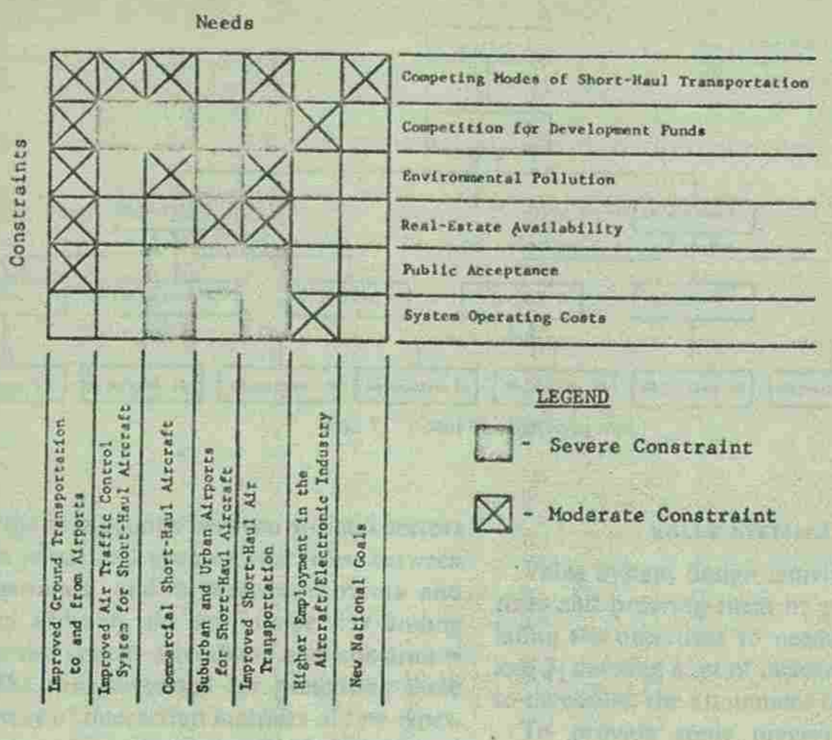


Fig. 3. Example of cross-interaction matrix.

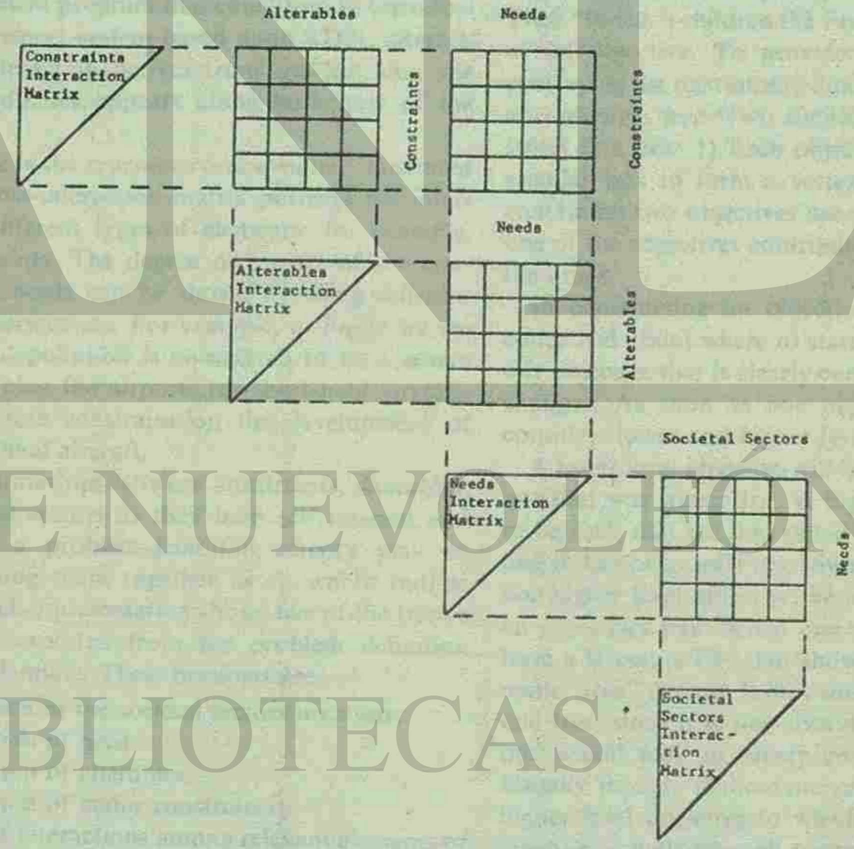


Fig. 4. Interactions of importance in problem definition for program planning.

[illegible]

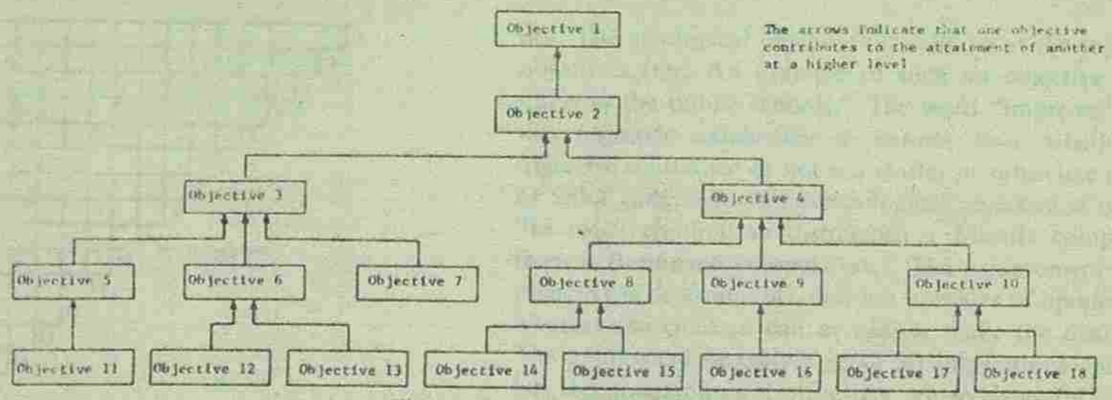


Fig. 5. Form of objectives tree.

A clear picture of the interactions between societal sectors and needs, between needs and systems alterables, between alterables and constraints, and between constraints and needs is desired. In addition, the self-interactions among societal sectors, needs, system alterables, and constraints should be clear. The tool suggested for presenting these interactions is an array of interaction matrices of two types.

The first type is the *self-interaction matrix* [2] illustrated in Fig. 2. This example illustrates two levels of dependency presented by the interactions of the objectives defined for a technical development program that could lead to introduction of an air-transport system based upon STOL aircraft. The name self-interaction derives from the fact that the same set of coordinates appears along both axes of the matrix.

The second type is the *cross-interaction matrix* illustrated in Fig. 3. The cross-interaction matrix portrays the interaction between different types of elements; for example, needs and constraints. The degree of impact of the constraints upon the needs can be shown by using different symbols at the intersections. For example, in Fig. 3 we see that environmental pollution is considered to be a severe constraint in planning the airports for short-haul aircraft, but only a moderate constraint on the development of commercial short-haul aircraft.

The overall relationships between constraints, alterables, needs, and societal sectors as they both self interact and cross interact in a problem-definition activity may be portrayed by linking them together as shown in outline form in Fig. 4. Such a presentation shows five of the twelve tangible products expected from the problem definition step of program planning. These products are:

1) a determination of the societal sectors involved;
2) an identification of need;
3) an identification of alterables;
4) an identification of major constraints;
5) description of interactions among relevant elements of the problem.

The use of such a presentation allows the planning group to keep track of the various elements that are considered during the problem definition process. More important, it provides a formal structure for problem definition, and, as will be seen, the rationale for defining objectives.

VALUE SYSTEM DESIGN LINKAGES

Value system design activity includes 1) defining objectives and ordering them in a hierarchical structure; 2) relating the objectives to needs, constraints, and alterables; and 3) defining a set of measures on the objectives by which to determine the attainment of objectives.

To provide some precision to program planning, a specific syntax has been developed for the form of an objective. An objective is defined as:

infinitive verb + object word or phrase + constraints.

Thus "to teach children the French language" is an example of an objective. To provide a structure for graphically portraying the relationship among objectives, one constructs an *objectives tree*. Two simple rules are employed to construct this tree: 1) Each objective is written within a rectangular box to form a vertex of the tree. 2) Two boxes containing two objectives are connected, if achievement of one of the objectives contributes directly to achievement of the other.

In constructing an objectives tree, one should not be concerned about where to start. Instead, one will start with any objective that is clearly contributory toward the desired changes. As soon as one objective is defined, one then considers lower and higher level objectives related to it.

A lower level objective will have to be contributory to the one that was stated first. A higher level objective will have to be such that the one stated first is contributory to it. If one thinks of at least one lower level objective and at least one higher level objective, he is on his way to constructing an objectives tree. When one is through, he will probably have a structure like that shown in Fig. 5, from which the name "tree" derives. It may turn out that there is more than one tree, since it is not always true that all the objectives one would seek to satisfy could be shown on one tree. Usually though, if there are separate trees, one can find a higher level objective to which all trees can be tied, thus creating a single (though perhaps rather leafy) tree.

A different way of portraying the information contained in an objectives tree is by way of a corresponding self-interaction matrix as shown in Fig. 6. Fig. 6 contains all of the information required to draw the objectives tree shown in Fig. 5 so long as we know that low-numbered objectives correspond to high-level objectives and vice versa. The self-

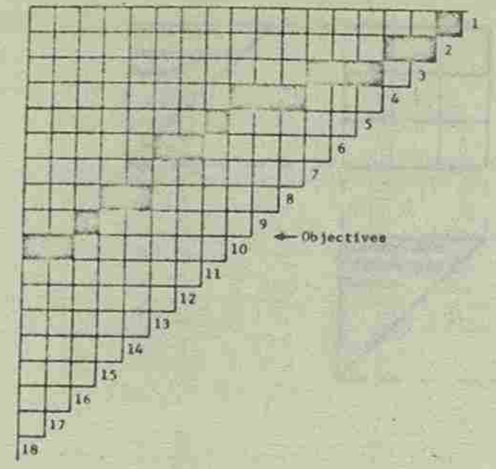


Fig. 6. Objectives self-interaction matrix corresponding to objectives tree shown in Fig. 5.

interaction matrix method of portrayal is not as clear as the objectives tree for viewing the relationships among objectives, but it incorporates significant advantages in relating objectives to constraints, alterables, and needs. The method suggested for portraying these relationships is the use of cross-interaction matrices as depicted in Fig. 7. This figure relates objectives to needs; to alterables, which can be modified to bring about attainment of the objectives; and to constraints, within which the objectives must be attained. In one concise figure, a complete outline of a rationale to support the objectives and a great deal of information needed to plan a program for attaining them appears.

A particular advantage of the method shown in Fig. 7 is the ease with which the interaction of the objectives can be traced through the needs back to the societal sectors with which the objectives interact. If the interactions are categorized as either significant or insignificant (i.e., binary), then a simple Boolean multiplication of the objectives × needs interaction matrix with the needs × societal sectors interaction matrix will result in an objectives × societal sectors interaction matrix.

The Boolean multiplication of cross-interaction matrices can be extended to the mathematical generation of some of the matrices shown in Fig. 7. For example, if the four cross-interaction matrices that lie closest to the self-interaction matrices were filled in by hand, the three remaining cross-interaction matrices shown in Fig. 7 could be generated mathematically. Such a formal procedure has considerable merit. Without it, one tends to end up with a set of cross-interaction matrices which are not mutually consistent and it is not always easy to spot the inconsistencies. Checking of logic is especially useful when the matrices form a loop as will be discussed later in relation to an example.

The need for defining a set of measures on the objectives by which to determine their attainment is an important concern in program planning. Too often, people define objectives without thought as to how they will measure their accomplishment. Upon examination of the objectives tree, one usually finds that some of the objectives are axiological (rooted in value judgments), while others are not. The axiological objectives usually lie at the top of the objectives tree. An example of such an objective is: "to improve the public schools." The word "improve" makes this objective axiological in nature, since whether this objective is attained or not is a matter of subjective opinion or value judgment. A nonaxiological objective is one like "to teach children to distinguish a Mozart composition from a Beethoven composition." The achievement of this objective is determinable, and not a matter of opinion as to whether the children can or cannot make the distinction. The axiological objectives serve an inspirational purpose, but the nonaxiological objectives are more useful in planning because they are more readily converted into planned activities.

One may examine the objectives tree to see which objectives are measurable, and how they may be measured. For the musical objective mentioned above, the measure is the agreement between the child's answer and the correct answer. The determination as to whether the public schools have been improved is vastly more difficult to make, and such an objective is virtually immeasurable within any reasonable cost. However, the attainment of lower level objectives that are contributory to that one may suggest that progress is being made.

For example, it should be possible to measure the attainment of an objective such as, "To improve the method of teaching reading to sixth graders to the extent that at least 70 percent of the students exceed the fiftieth percentile performance on a standardized sixth-grade reading achievement test." The corresponding objective measure could be "Percent of sixth-grade students, whose performance exceeds the fiftieth percentile performance on a standardized sixth-grade reading achievement test."

The total process of measurement involves more than just the selection of the measure or unit by which the attainment of objectives will be assessed. Often, as in the above example, a threshold for judging acceptable performance can be defined and built into the objective and objective measure. The balance of the process of measurement includes planning for how the data required for evaluation are to be *sensed* and how they are to be analyzed to generate an *indication* on the selected measurement scale. In the above example, planning for the sensing function would involve selection of the achievement test, planning when, to which students, and under what conditions the test would be administered and planning for how the resulting tests would be interfaced with the test-scoring activity. Planning the indicator function would involve selection of procedures for analyzing the test scores and reducing them to standard achievement scores in a timely and efficient manner.

Thus the planning of objectives and objectives measures is tightly interwoven with the process of determining how the measures are to be obtained, i.e., how the data are to be sensed, and how the indication on the scale of measurement is to be attained.

The measures of objectives may be conveniently related to the objectives through the use of a cross-interaction matrix as indicated in Fig. 8. Measures 1 and 2 relate to the attainment of objective 6; measure 3 to the attainment of

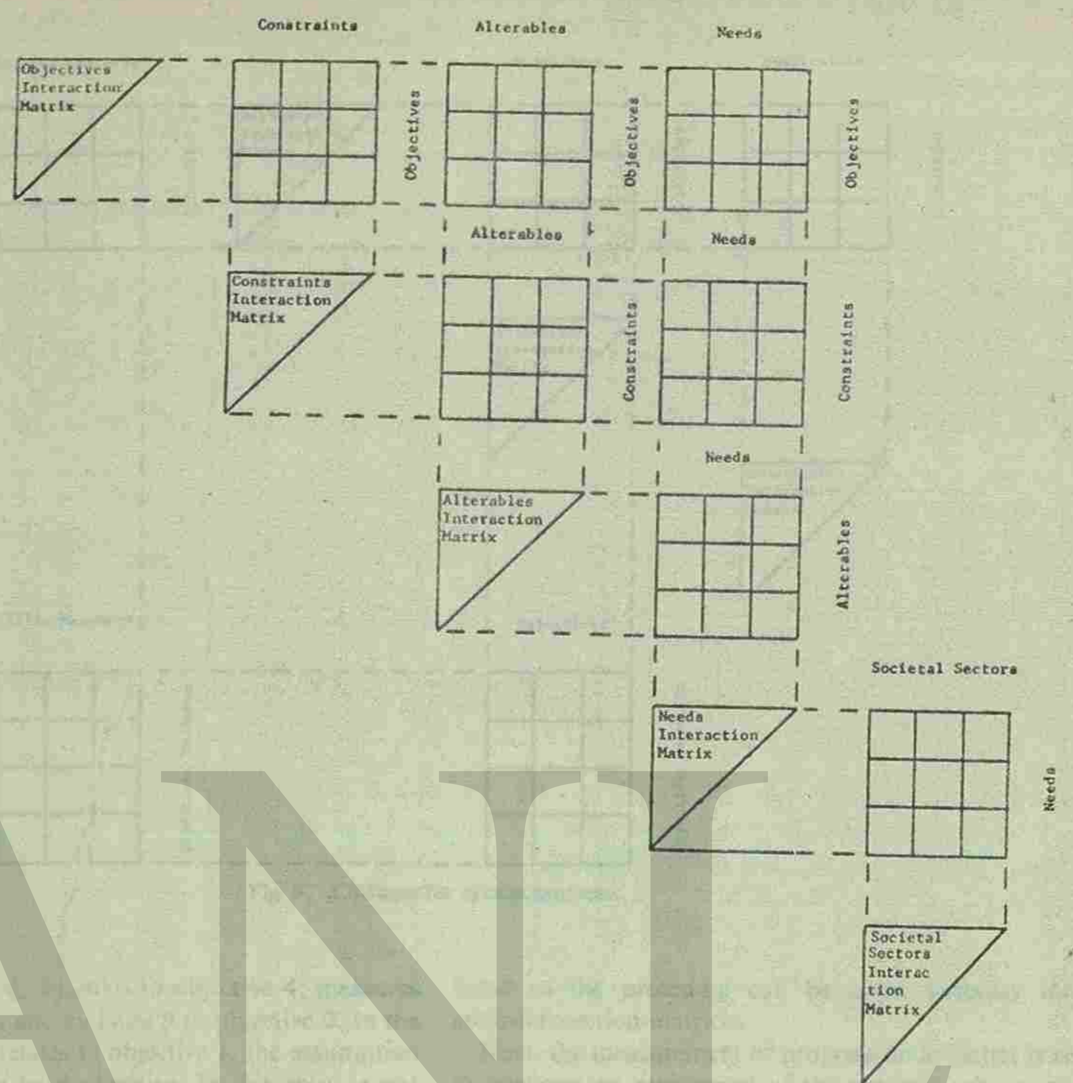


Fig. 7. Interaction of objectives with constraints, alterables, needs, and societal sectors.

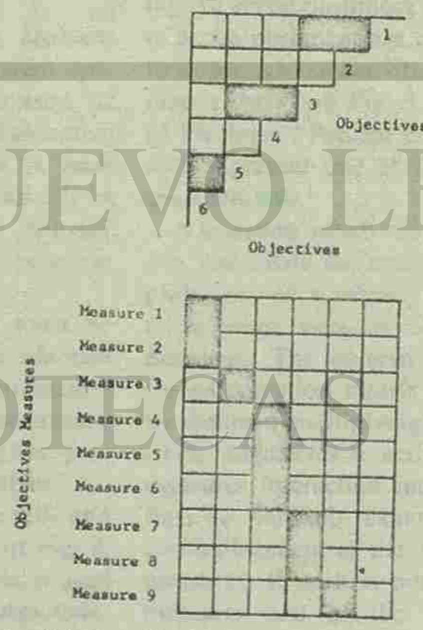


Fig. 8. Relating objectives measures to objectives.

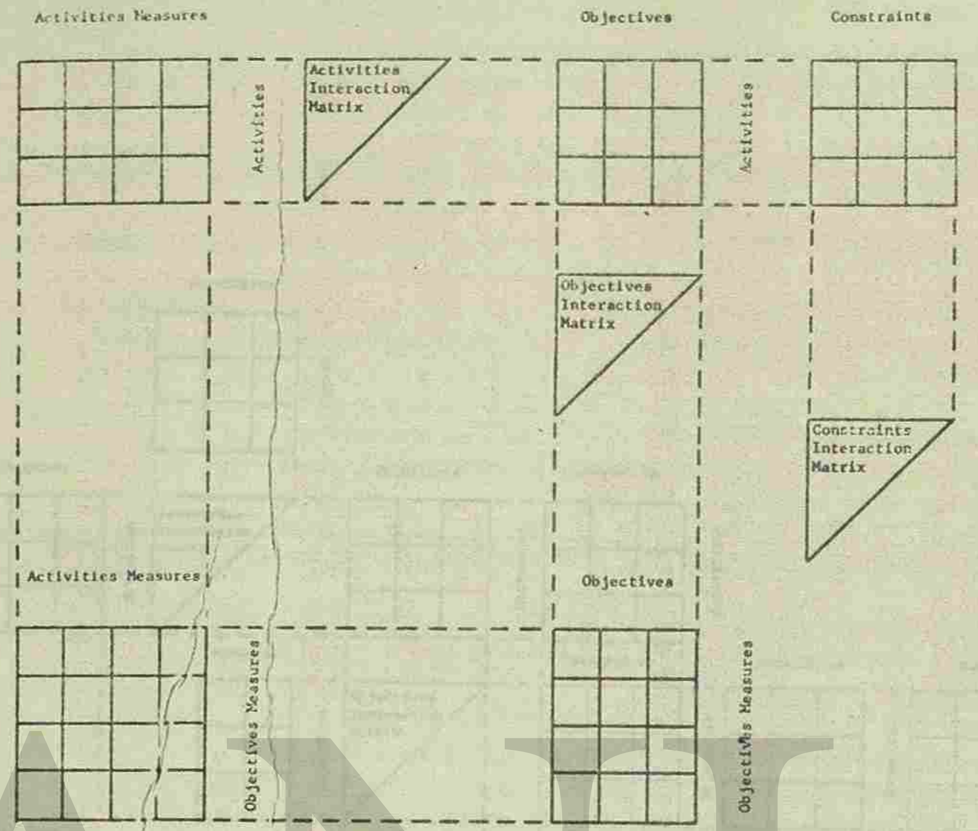


Fig. 9. Linkages for system synthesis.

bjective 5; measures 4, 5 and 6 to objective 4; measures and 8 to objective 3; and measure 9 to objective 2. In the xample, no measure relates to objective 1, the assumption eing that the highest level objective, in this case, is not irectly measurable.

SYSTEM SYNTHESIS LINKAGES

Hall's matrix, Fig. 1, shows that following problem efinition and value system design comes the system synthesis step. System synthesis activities are directed at nswering the following questions. What are the alternative pproaches for attaining each objective? How is each lternative approach described? The answers are usually in he form of a series of activities which form a plan for valuating alternative approaches for attaining the program bjectives.

Three major linkages to the preceding steps must be iven visibility. 1) The relationship between the planned ctivities and the program objectives. 2) The interaction etween the planned activities and the program constraints. 3) The measurement system required for relating the progress on the activities to the attainment of objectives.

Again, when faced with a linkage problem, the self- and ross-interaction matrices are used as illustrated in Fig. 9. The activities × objectives cross-interaction matrix is used o relate the proposed activities to specific objectives. Similarly, the interactions of the constraints with the ctivities are illustrated by the activities × constraints nteraction matrix. Thus the first two of the major linkages listed in the preceding can be given visibility through cross-interaction matrices.

Next, the measurement of progress on activities is related to progress on attainment of the program objectives. Development of a set of objectives measures was discussed previously. An analogous procedure is followed in measuring the accomplishment of activities. One or more measures of accomplishment are defined for each activity and related to it through the activities × activities measures interaction matrix shown in Fig. 9. Often, the activities measures are of the form "Percent completion of ⋯" where the three dots represent one of the products of the activity under consideration.

A question which management is likely to ask is "How can you relate the attainment of objectives to the accomplishment of activities?" One method is to examine the relationship between activities measures and objectives measures. The objectives measures × activities measures cross-interaction matrix can be generated mathematically by Boolean multiplying the objectives measures × objectives, objectives × activities, and activities × activities measures interaction matrices. The resulting matrix must then be carefully examined to ensure that measures of accomplishment of the activities do relate to the objectives measures. If such is not the case, a reexamination of all measures and of the activities × objectives interaction matrix must be made. Either the matrix must be changed or the measures redefined so the activities measures relate to the attainment of objectives.

Fig. 10. Program planning linkages.

To this point, a series of related linkages for the problem definition, value system design, and system synthesis steps of program planning has been discussed. An overall view of a program as planned at the end of the system synthesis step is obtained by combining Figs. 7 and 9 as in Fig. 10. Added to Fig. 10 is an objectives × agencies interaction matrix to portray which government or industrial groups have an interest in the defined objectives and an agents × activities interaction matrix to identify the agents responsible for conduct of each activity.

One concise figure portrays the major products of initial program planning efforts and their inter- and intrarelationships, and provides a useful tool for keeping track of subsequent progress as action is taken to implement the activities and attain the program objectives. Fig. 11 illustrates an application of a chain of binary interaction matrices. This chain was used to relate a proposed program directed at identifying technology development areas critical to STOL aircraft to the more comprehensive problem of implementing commercial STOL aircraft service as an integral part of the U.S. national transportation system. At the right side of Fig. 11 are sets of needs, alterables, and constraints associated primarily with the comprehensive problem within which the problem of identifying needed technology development is embedded. The activities and all but the two objectives at the top of the list shown on the self-interaction matrix in the center of the figure relate to the proposed program for identifying technology developments needed to further STOL system development. The top two objectives relate to the comprehensive problem.

In planning this proposed program, the illustrated set of interaction matrices was used both to develop a perspective of the proposed program in relation to the larger problem, and to assure that the program would support the objectives of the larger problem taking into account the needs, alterables, and constraints associated with implementing a commercial STOL system.

For example, one of the proposed activities shown in Fig. 11 is "Synthesize STOL vehicle system configuration using Monte Carlo avionics evaluation program (AEP) to satisfy mission performance goals." This activity is shown in a box at about the center of the list of activities in Fig. 11. As indicated by the activity × activities measures cross interaction labeled "*I*," the activity measure associated with this activity is "percent completion of definition of vehicle system configurations." The activity was designed to attain the objective "To synthesize STOL systems configurations to satisfy mission performance goals" as indicated by the cross interaction labeled "*G*" on the activities × objectives cross-interaction matrix.

By following around the loop of interaction matrices at the left side of Fig. 11, one sees that the interaction labeled "*J*" in the objectives measures × activities measures cross-interaction matrix relates the activity measure to the objective measure "percent completion of mission performance goals definition" which, through interaction *K*, is related to the objective mentioned above. In this way, the activity and its measure of accomplishment is tightly connected to the attainment of a corresponding objective or objectives and their measures of attainment.

One can also see from Fig. 11 how the proposed activities relate to the more comprehensive problem. For example, the aforementioned activity must take into account the constraint "system operating costs" since it is directly related to that constraint by the activities × constraint interaction labeled "*H*." In turn, through the cross interactions labeled "*B*" and "*A*," it is seen that one of the major alterables to consider in conducting the activity is "aircraft performance characteristics" and that the activity relates to the need for "commercial short-haul aircraft."

The cross interaction labeled "*F*," "*E*," and "*D*" point out, as would be expected, that the needs, alterables, and constraints previously discussed also affect the objective "To synthesize STOL system configuration to satisfy mission performance goals." The agencies responsible for attaining objectives and the agents responsible for accomplishing activities are also contained in Fig. 11. For the objective and activity discussed, these responsibilities are indicated by cross interactions "*M*" and "*L*," respectively.

The system analysis and optimization steps shown in Fig. 1 are generally concerned with reducing the number of program alternatives through the application of a wide variety of analysis procedures that are highly contextual. For that reason, they will not be discussed in this paper; but those procedures must be planned to produce an output which is consistent with the input requirements of the subsequent decision-making step.

DECISION MAKING IN PROGRAM PLANNING

During the system synthesis step in program planning, there will have been defined measures for determining the attainment of program objectives. Also, a set of activities and activities measures for guiding subsequent activities toward the development of a complete program plan will have been defined. The questions that arise are "What criteria will be used to select projects for development?" and "What information must be obtained in the system analysis and optimization steps in order to compare alternative projects?"

Four major factors concern the decision maker in evaluating alternative projects for possible further development. First, he must determine that the scopes of the projects under consideration are consistent with corporate or agency policy. This determination can be made by evaluating how well the candidate projects satisfy the program objectives which are assumed to be in consonance with corporate or agency policy. (A program whose scope is not consistent with corporate or agency policy would be rejected on the basis of this alone.) Those projects that pass this initial screening are then rated in terms of the remaining three factors discussed below.

The second major factor is the comparative economics of the alternative projects. The analysis should look at the long-range project costs, not just the development costs or the cost required to get a system into operation. Total life-cycle costs appear to be an appropriate economic measure since they include all system costs and put the cost analysis for each alternative project on an equitable basis for comparison.

The third factor, risk associated with projects, has received considerable emphasis recently, particularly by the Department of Defense. At least two types of risks should be considered in selecting projects. The first is the "risk due to nature." By this is meant the probability that a project will not succeed because the technical requirements are incompatible with basic physical laws. The second risk is the "risk due to technology." This risk is the probability that a project will be unsuccessful because it requires technology beyond the current state of the art even though no laws of nature appear to be limiting. Other types of risks would be appropriate in assessing programs with high-social content.

The fourth major factor to be considered by the decision maker is that of benefits which would result from the pursuit of each alternative project. Decision makers are faced with the problem of evaluating the worth of each project under consideration. Worth assessment [3] is a formal procedure for assessing the worth of discrete alternatives. It appears to be well suited to providing a "benefit" input.

Criterion Function

In comparing alternative projects, it is desirable to combine the major evaluation factors into a single, scalar-valued criterion function. Such a function must be reasonably general and easy to interpret if it is to have wide application The function suggested here is derived by multiplying two parts to yield its value. The first part is the probability of being able to successfully carry out a candidate project, calculated by multiplying one minus the risk due to nature by one minus the risk due to technology. The second part of the criterion function is a cost-benefit factor composed of the weighted sum of inverse normalized project cost and project worth.

The criterion function is calculated for each alternative project. The criterion function is expressed as

$$Q_i = (1 - R_{n_i})(1 - R_{t_i})(aC_i^{0} + bV_i)$$

where

Q_i value of criterion function for ith project; for $i = 1,2,\cdots,q$, where q is the total number of projects under consideration;

R_{n_i} risk of nature to the ith project $= 1 - \prod_k(1 - r_{k,i}^{\,n})$, where $r_{k,i}^{\,n} = (k = 1,2,\cdots,m)$ is the risk due to nature to the kth, project characteristic of the ith project, where m is the total number of project characteristics for which risk due to nature is estimated;

R_{t_i} risk of technology to ith project $= 1 - \prod_k(1 - r_{k,i}^{\,t})$, where $r_{k,i}^{\,t} = (k = 1,2,\cdots,p)$ is the risk due to technology to kth project characteristic of the ith project, where p is the total number of project characteristics for which risks due to technology is estimated;

C_i^{0} normalized inverse life-cycle cost of ith alternative project $= (1/C_i)\min_i C_i$, where C_i is the estimated cost of ith alternative project;

a weighting factor for normalized inverse life-cycle costs;

b $(1 - a) =$ weighting factor for worth scores;

V_i worth score for ith alternative project. ($0 \le V_i \le 1$; $i = 1,2,\cdots,q$).

The criterion function combines the risk factors with a weighted average of inverse normalized life-cycle cost and worth assessment score. The ideal configuration/program alternative combination would have zero risk due to nature, zero risk due to technology, the least life-cycle cost of any alternative project, and a worth score of 1.0. In this ideal situation, the criterion function would have a value of 1.0.

If the risk due to nature or the risk due to technology for any project characteristic is 1 (that is, the characteristic is judged to be impossible to meet), then the probability of successfully developing the configuration under consideration is zero and its criterion function has a zero value. Since the risk due to nature and risk due to technology will each be greater than or equal to the maximum risk of each contributing risk factor, careful consideration must be given to the estimation of each risk factor. The computation of risk draws attention to those factors that would potentially prevent project success and helps ensure that a critical factor is not ignored.

Weighting factors "a" and "$b = (1 - a)$" allow changing the relative importance of the cost and worth factors. The choice of values for a and b will be governed by such factors as confidence in the cost analysis (e.g., low confidence; make "a" small), the magnitude of the costs relative to total resources, and the significance of the benefits that could be used depending upon the sensitivity to cost. For example,

$$C_i^{0} = \frac{\max_i C_i - C_i}{\max_i C_i - \min_i C_i}$$

provides a linear weighting to cost variation between the maximum and minimum cost projects. The cost normalization scheme suggested earlier provides considerable sensitivity to cost variations near the minimum cost and much lower sensitivity and a lower weight to costs much greater than the minimum cost. Numerous other ways of normalizing the project cost estimates are available and should be examined in the context of the particular problem under study.

The numeric value of the criterion function at the program planning phase is normally quite small. This observation reflects the uncertainties associated with projects during an early planning phase. In particular, technically demanding projects will have low criterion values due to the risks involved. The absolute value of the criterion function is not as important, however, as the relative value for each alternative project.

Project selections are made on the basis of the program scope being consistent with corporate or agency policy, as mentioned earlier, and the relative values of the criterion function for each project. If the criterion values are low, the reasons for this should be considered and action taken in the subsequent project planning phase to investigate the reasons underlying the low values.

Evaluation of Risks

In the program planning phase, the evaluation of risks inherent in pursuing various alternative projects is usually dependent upon expert opinion and subjective judgment rather than detailed analyses. A typical approach to risk evaluation is to make a detailed breakdown of the functional performance factors forecasted for each project and to call in experts in each of the functional areas to assess risks due to nature and technology associated with attaining the projected performance. Care should be taken in defining the functional performance factors to assure that they are all of about the same level of importance and that the risks are due to independent causes. This care is suggested since the value of the criterion function is equally sensitive to each risk associated with each factor and the risk calculation assumes independence of risks.

High-risk performance factors should be flagged so that subsequent project planning calls for an early second assessment of the high-risk performance factors for each of the projects selected for further development.

Worth Assessment

Worth assessment is a formal procedure for assessing the worth of discrete alternatives in the decision-making environment. The following is a brief outline of a worth assessment procedure developed by Miller, [3].

A. Define worth criteria.
   List criteria for worth assessment ensuring list:
   1) contains all significant criteria;
   2) contains only mutually exclusive criteria;
   3) contains only criteria of major significance;
   4) contains only worth independent criteria.

B. Develop hierarchical structure of worth assessment criteria.
   Break down high-level worth assessment criteria into one or more lower level criteria which contribute to the high-level criteria.

C. Develop performance measures.
   Select a single physical-performance measure for each lowest level worth assessment criterion in the hierarchical structure.

D. Develop worth relationships between performance measures and lowest level worth assessment criteria.
   Define a scoring function to assign a unique worth score in points to every possible value of a physical performance measure. A scoring function is defined, either explicitly or implicitly for every lowest level worth assessment criterion.

E. Develop a single overall index of worth.
   Define an additive weighting function with constant trade-off weights to combine the lowest level criteria worth scores.

The index of worth is devoid of any risk and/or uncertainty. It assumes that the project, activity, or performance consequence being evaluated will occur *for certain* and the process of assigning a worth number provides no mechanism for reflecting perceived trade-offs between the worth of an outcome, conditional upon its actual occurrence, and the variable risk or uncertainty surrounding its occurrence. The index of worth appears to complement the Criterion Function which has separate risk factors built into it.

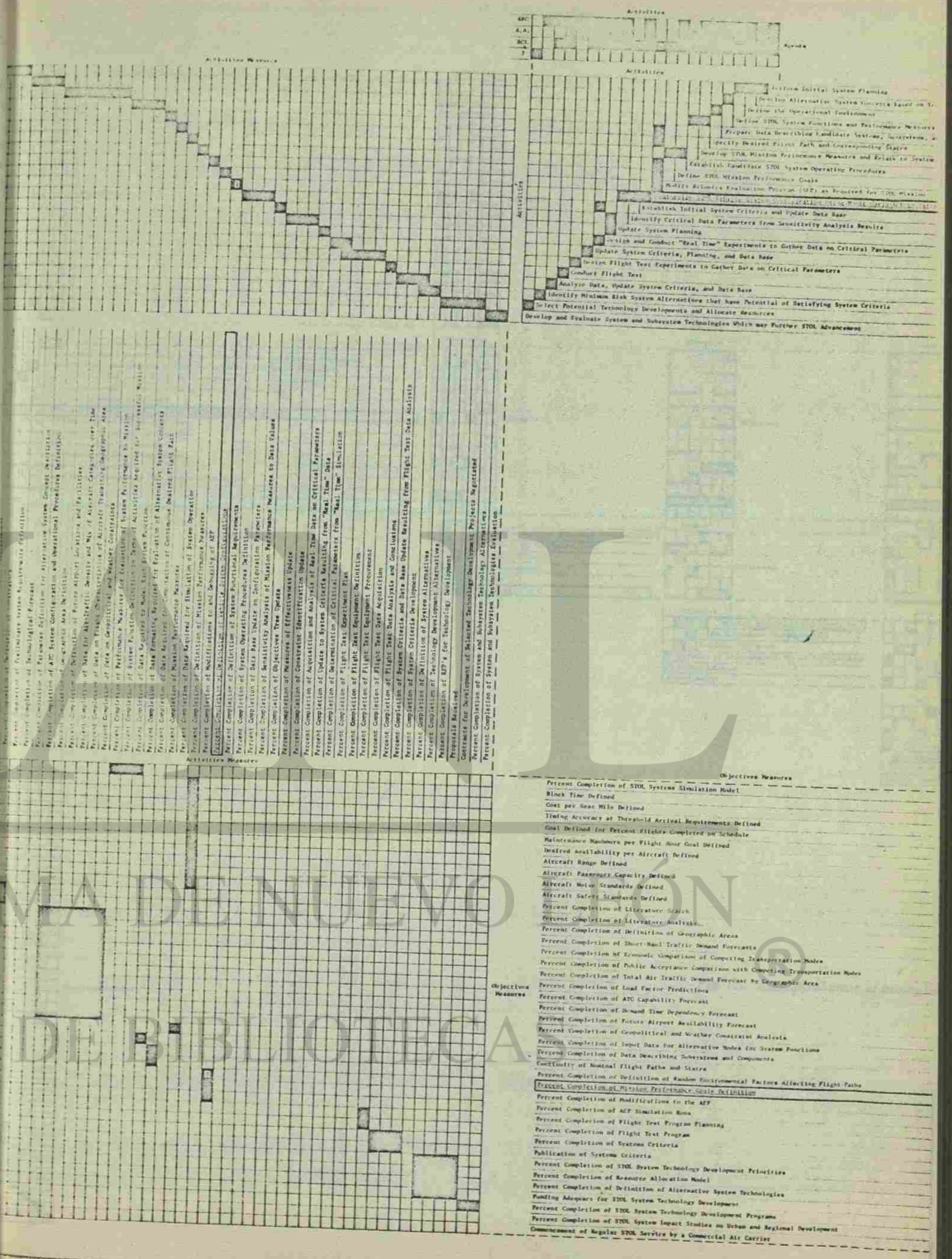
Miller's worth-assessment technique relates to program planning in another way. The objectives measures provide a baseline upon which to develop the worth assessment criteria and performance measures of each alternative project. Also, the objectives interaction matrix and other interaction matrices that relate the objectives to constraints, alterables, needs, and societal sectors provide considerable visibility to the relative importance of the worth assessment criteria. The task of weighting the worth assessment criteria can then be done in relation to their contribution to the related needs, constraints, etc.

As part of the worth assessment procedure, the relation of the performance measures to the needs should be examined and used to develop the scoring functions that relate the performance measure of each lowest level performance criterion to a worth score. The relation of performance measures to needs should also be considered when developing the adjusting factors to compensate for the fact that performance measures may not adequately represent the performance criteria. Worth assessment is recommended as a formal approach to evaluating the comparative worths of alternative projects. The resulting worth scores satisfy the requirement of the criterion function for a worth score for each alternative project.

SUMMARY

The systems engineering steps required to do program planning are not related only to their neighboring steps nor are they carried out in a sequential temporal order. Rather, they form a logical set of operations that are highly interrelated and consequently must be continually reviewed with respect to each other as program planning progresses. In planning a complex program, the linkages between these operations tend to become buried in the complexity of the problem rather than being emphasized and given visibility. The set of interaction matrices illustrated in Figs. 10 and 11 provides a visible means of organizing and managing program planning activities.

Decision making will always require the subjective input of experienced managers. Nevertheless, formal evaluation techniques are helpful in assessing the relative merits of alternative projects that comprise a program. The criterion function described in this paper combines the factors of


Activities
ARC
A.A.
BCL
Agenda
Activities
Activities Measures
Perform Initial System Planning
Develop Alternative System Concepts Based on S…
Define the Operational Environment
Define STOL System Functions and Performance Measures
Prepare Data Describing Candidate Systems, Subsystems, a…
Specify Desired Flight Path and Corresponding States
Develop STOL Mission Performance Measures and Relate to System
Establish Candidate STOL System Operating Procedures
Define STOL Mission Performance Goals
Modify Avionics Evaluation Program (AEP) as Required for STOL Mission
Establish Initial System Criteria and Update Data Base
Identify Critical Data Parameters from Sensitivity Analysis Results
Update System Planning
Design and Conduct "Real Time" Experiments to Gather Data on Critical Parameters
Update System Criteria, Planning, and Data Base
Design Flight Test Experiments to Gather Data on Critical Parameters
Conduct Flight Test
Analyze Data, Update System Criteria, and Data Base
Identify Minimum Risk System Alternatives that have Potential of Satisfying System Criteria
Select Potential Technology Developments and Allocate Resources
Develop and Evaluate System and Subsystem Technologies Which may Further STOL Advancement
Percent Completion of Preliminary System Requirements Definition
Percent Completion of Technological Forecast
Percent Completion of Parameter Definition for Alternative System Concept Descriptions
Percent Completion of ATC System Configuration and Operational Procedures Definition
Percent Completion of Geographic Area Definition
Percent Completion of Definition of Future Airport Locations and Facilities
Percent Completion of Data for Alternative Density and Mix of Aircraft Categories over Time
Percent Completion of Data in Flight Characteristics of Aircraft Traversing Geographic Area
Percent Completion of Data on Geopolitical and Weather Constraints
Percent Completion of Performance Measures for Evaluation of System Performance to Mission
Percent Completion of System Functions Definition in Terms of Activities Required for Successful Mission
Percent Completion of Data Required to Model Each System Function
Percent Completion of Data Formatting Required for Evaluation of Alternative System Concepts
Percent Completion of Data Required for Determination of Continuous Desired Flight Path
Percent Completion of Mission Performance Measures
Percent Completion of Data Required for Simulation of System Operation
Percent Completion of Definition of Mission Performance Measures
Percent Completion of Modifications to and Debugging of AEP
Percent Completion of Definition of Vehicle System Configuration
Percent Completion of Definition of System Functional Requirements
Percent Completion of System Operating Procedures Definition
Percent Completion of Data Base Update on Configuration Parameters
Percent Completion of Sensitivity Analysis of Mission Performance Measures to Data Values
Percent Completion of Objectives Tree Update
Percent Completion of Measures of Effectiveness Update
Percent Completion of Constraint Identification Update
Percent Completion of Acquisition and Analysis of Real Time Data on Critical Parameters
Percent Completion of Update to System Criteria Resulting from "Real Time" Data
Percent Completion of Determination of Critical Parameters from "Real Time" Simulation
Percent Completion of Flight Test Experiment Plan
Percent Completion of Flight Test Equipment Definition
Percent Completion of Flight Test Equipment Procurement
Percent Completion of Flight Test Data Acquisition
Percent Completion of Flight Test Data Analysis and Conclusions
Percent Completion of System Criteria and Data Base Update Resulting from Flight Test Data Analysis
Percent Completion of System Criteria Development
Percent Completion of Definition of System Alternatives
Percent Completion of Technology Development Alternatives
Percent Completion of RFP's for Technology Development
Proposals Received
Contracts for Development of Selected Technology Development Projects Negotiated
Percent Completion of System and Subsystem Technology Alternatives
Percent Completion of System and Subsystem Technologies Evaluation
Activities Measures
Objectives Measures
Percent Completion of STOL Systems Simulation Model
Block Time Defined
Cost per Seat Mile Defined
Timing Accuracy at Threshold Arrival Requirements Defined
Goal Defined for Percent Flights Completed on Schedule
Maintenance Manhours per Flight Hour Goal Defined
Desired Availability per Aircraft Defined
Aircraft Range Defined
Aircraft Passenger Capacity Defined
Aircraft Noise Standards Defined
Aircraft Safety Standards Defined
Percent Completion of Literature Search
Percent Completion of Literature Analysis
Percent Completion of Definition of Geographic Areas
Percent Completion of Short-Haul Traffic Demand Forecasts
Percent Completion of Economic Comparison of Competing Transportation Modes
Percent Completion of Public Acceptance Comparison with Competing Transportation Modes
Percent Completion of Total Air Traffic Demand Forecast by Geographic Area
Objectives Measures
Percent Completion of Load Factor Predictions
Percent Completion of ATC Capability Forecast
Percent Completion of Demand Time Dependency Forecast
Percent Completion of Future Airport Availability Forecast
Percent Completion of Geopolitical and Weather Constraint Analysis
Percent Completion of Input Data for Alternative Modes for System Functions
Percent Completion of Data Describing Subsystems and Components
Continuity of Nominal Flight Paths and States
Percent Completion of Definition of Random Environmental Factors Affecting Flight Paths
Percent Completion of Mission Performance Goals Definition
Percent Completion of Modifications to the AEP
Percent Completion of AEP Simulation Runs
Percent Completion of Flight Test Program Planning
Percent Completion of Flight Test Program
Percent Completion of Systems Criteria
Publication of Systems Criteria
Percent Completion of STOL System Technology Development Priorities
Percent Completion of Resource Allocation Model
Percent Completion of Definition of Alternative System Technologies
Funding Adequacy for STOL System Technology Development
Percent Completion of STOL System Technology Development Programs
Percent Completion of STOL System Impact Studies on Urban and Regional Development
Commencement of Regular STOL Service by a Commercial Air Carrier

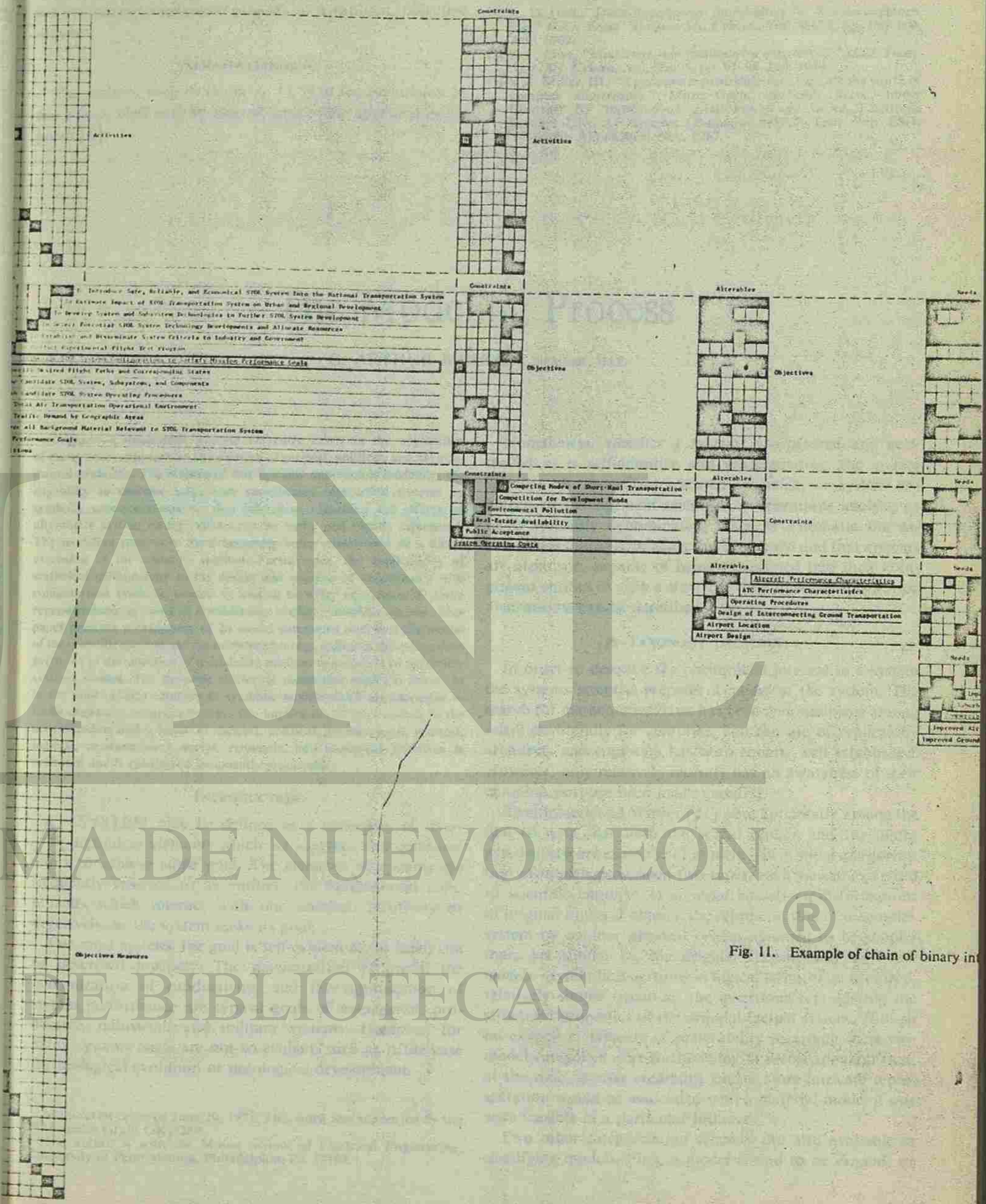


Fig. 11. Example of chain of binary int

risk, worth, and cost into a single, scalar-valued function for comparing alternative projects in a rational, objective manner.

ACKNOWLEDGMENT

The authors wish to thank A. D. Hall for permission to use Fig. 1, Hall activity matrix, which also appeared in his paper [1].

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The Modeling Process

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Abstract—Considerable interest currently exists in the application of the systems approach to the solution of societal, political, and environmental problems. The essence of this systems approach is modeling, the capability to describe large-scale complicated interactive systems by symbolic representations so that infereaces regarding the effects of alternative system configurations can be easily and rapidly structured. The modeling process is itself becoming better understood as a direct extension of the scientific method. Furthermore, the applicability of statistical methodology to the design and analysis of experiments with computerized symbolic models is leading to wider acceptance of these representations as tools of considerably credible scientific stature. This paper presents a taxonomy of 24 model categories and, in a discussion of the scientific method and the modeling process, indicates the evaluations pertinent to the selection of a modeling medium appropriate to particular systems studies. The dynamic stochastic simulation model is shown to be the most general category of symbolic models which are amenable to facile organized experimentation. The application of such models to the understanding and solution of societal, political, psychological, medical, judicial, environmental, social, economic, and biological problems is indicated and is considered imminently practicable.

INTRODUCTION

A SYSTEM may be defined as a collection of interdependent elements which act together in a collective effort to achieve some goal. The elements of systems are frequently referred to as entities, the fundamental components which interact with one another, positively or negatively, as the system seeks its goal.

For most systems the goal is self-evident or, at least, can be described precisely. The maximization of profit, the maximization of productivity, and the optimization of system performance are typical goals of managerial, productive, industrial, and military systems. However, for many systems goals are not so evident, such as is the case for biological evolution or ontological development.

Nonetheless, whether a system is organized and controlled or is self-adaptive and self-regulating, the *system scientist* (or operations research specialist, or system engineer, or management scientist, or operations analyst, as he is variously denominated) takes as axiomatic the assumptions that system goals can be defined and that systems are atomistic, capable of being dissociated into their component entities in such a way that their interactive behavior mechanisms can be described.

A TAXONOMY OF MODELS

In order to describe the phenomena internal to a system the systems scientist prepares a *model* of the system. The search for mathematical laws has been commonplace among scientists literally for centuries, and the use of replicas by architects and engineers has been equally well established. However, only relatively recently has an awareness of their common purpose been made manifest.

Rosenblueth and Wiener [27] were apparently among the first to note that both the scaled replica and the mathematical law are examples of models. Their initial categorization of models prescribed two types, each viewed as an aid to scientific enquiry: 1) *material models*—transformations of original physical objects, the representation of a complex system by another physical system assumed to be simpler than, yet similar to, the original system; and 2) *formal models*—symbolic assertions in logical terms of an idealized, relatively simple situation, the assertions representing the structural properties of the original factual system. Though no explicit statements of preferability regarding these two model categories were forthcoming, it seems apparent that, at the time, greater credibility and a more intricate representation would be associated with a material model if one were feasible in a particular instance.

Two other categorization schemes are also available in classifying models. First, a model is said to be *dynamic* or

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static depending upon whether its features or symbols do or do not, respectively, alter perceptibly with time. This classification is a cross-categorization scheme with respect to the Rosenblueth–Wiener taxonomy, so that one may have both dynamic and static material models as well as dynamic and static formal models. To wit, a statue of Benjamin Franklin is a quite static material model, as is a photograph and a weather map; whereas, a puppet show, a critical dosage test, a mobile orrery, and a planetarium show are all dynamic material models of physical phenomena. Exemplary static formal models include Newton's inverse square law and the expression for the equilibrium queue length in a nonpreemptive *M/M/*1 queue.[1] Typical dynamic formal models are Lanchester's laws[2] and the autoregressive time series.

One should note in passing that particular problem formulations, or classes of formulations, do not necessarily fall distinctly into the same cross-category; e.g., a linear programming model, though definitely of the formal model variety, may be either dynamic or static depending upon whether or not the optimization is conducted over time explicitly.

A second cross-classification scheme for models is concerned with the predictability of the model's final state. A model is said to be *stochastic* if it contains intrinsic probabilistic or random elements which affect the outcome or response of the model; otherwise, the model is *deterministic*. The cross-classification of these model types with the four already mentioned implies a total of eight primary model categories. Examples of each include those which have been mentioned: the statue, road maps, or scale model (material–static–deterministic); the weather map or biological critical dosage test (material–static–stochastic); the model train set or planetarium shows (material–dynamic–deterministic); the puppet show or the genetic experiment with *Drosophila* (material–dynamic–stochastic); Ohm's law or Newton's inverse square law (formal–static–deterministic); the equilibrium queue length (formal–static–stochastic); Lanchester's laws (formal–dynamic–deterministic); and the autoregressive time series (formal–dynamic–stochastic).

EVOLUTION OF MODEL TYPES

At approximately the same time as the appearance of the initial categorization of models by Rosenblueth and Wiener, two important scientific fields were developing: computer science and a systems (or operational research) methodology. The computer was to have profound effect on models of both the material and formal varieties (as we shall see), and the development of the systems methodology has required an increasing need for greater detail and more realistic representations in models.

The systems methodology has relied more and more on the electronic computer. For example, the analog electronic computer, made practicable by the development of a sufficiently accurate electronic operational amplifier, permitted one to provide a physical representation for specific formalized expressions; thus a set of interrelated time-dependent differential equations (such as Lanchester's laws) could be "solved" by tracing appropriate electrical properties of an *ad hoc* electrical network as time evolved. (See Ragazzini *et al.* [26].)

That such analogue[3] models were possible was realized even as early as a century ago soon after pairs of formal models, each originally derived for a specific physical phenomenon, were noted to be of the same form: e.g., the applicability of an inverse square law in both gravitational and electrical field theories implied that one might well be capable of miming a gravitational phenomenon by an electrical device.

In their ground-breaking volume on operations research, Churchman *et al.* [6] defined models as "representations of the system under study, a representation which lends itself to use in predicting the effect on the system's effectiveness of possible changes in the system" and categorized models into three types: 1) *iconic*—those which pictorially or visually represent certain aspects of a system; 2) *analogue*—those which employ one set of properties to represent some other set of properties which the system being studied possesses; and 3) *symbolic*—those which require mathematical or logical operations and which can be used to formulate a solution to the problem at hand. From the discussion surrounding this classification, it seems apparent that the iconic models are material models in the Rosenblueth–Wiener sense and that the class of symbolic models was to be the equivalent of the formal class of models (*à la* Rosenblueth–Wiener). The analogue model was to have been a class "between" the other categories, which were themselves to be distinguished primarily from the view that iconic models were intended to be *descriptive*, yet symbolic models *explanatory*, of the phenomenon or system under study.

Subsequently, Sayre and Crosson [28], searching for a representational mode for an artificially intelligent device, categorized models as 1) *replications*—those which display a significant degree of physical similarity in all three dimensions between the model and the modeled; 2) *formalizations*—symbolic models in which none of the physical characteristics of the modeled are reproduced in the model itself *and* in which the symbols are manipulated by a well-formed discipline such as mathematical logic; and 3) *simulations*—the class of symbolic models, all of whose symbols are *not* manipulated by a well-formed discipline (such as mathematics or mathematical logic) in order to arrive at a particular numerical value or at an analytic solution or expression.

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[1] The shorthand refers to Kendall's classification of queues [14]. An *M/M/*1 queue is a single-server queue with Markovian arrival pattern and exponentially distributed service times.

[2] Lanchester's laws describe the dynamics of the battlefield, one of the earliest recognized contributions to the systems or operations research approach. (See Newman [23, pp. 2138–2159].)

[3] The French orthography is employed so as to distinguish between this type of physical model (*analogue*) and the *analog* type of computer, by which many analogue models are implemented.

There are several significant points regarding the Sayre–Crosson categorization scheme. First, no provision is made for the inclusion of the analogue model, though the fact that the many analog computer implementations were essentially "substitutions" for other physical phenomena (which happen to be described by the same formal model) could have led to the dismissal of this model type. Second, the class of replications specifically forbade dimensional reductions, thereby excluding photographs, maps, cinemas, and the planetarium show as replicas of modeled phenomena.

Finally, and most importantly, Sayre and Crosson distinguished between two types of symbolic models. Whereas Churchman *et al.* had essentially equated their symbolic category of models with the formal models of Rosenblueth and Wiener, Sayre and Crosson recognized that the programmed electronic digital computer was making possible the construction and implementation of *algorithmic* or *operational* models more general than the formal symbolic models which required the use of well-formed mathematical disciplines for the manipulation of the model's symbols. These more general models, typified by a logically connected sequence of machine-comprehensible statements (or *algorithmic programs*), no longer required the use of mathematical (or mathematical logical) operations for their manipulation, but merely a coherent consistent outline of procedures to be followed, either in manipulating or in assigning successively values to the symbols constituting the model. These algorithmic models were termed *simulations* by Sayre and Crosson.

Unfortunately, the term "simulation" had been previously adopted by users of analog electronic computers to describe their use of such devices in miming formalized equivalent expressions for other time-dependent physical phenomena. (See, e.g., McLeod [18].) Moreover, many authors tend to identify the term simulation with any computerized dynamic model (cf: Kiviat [15] and Gordon [13]).

The semantic difficulties become further confounded whenever one attempts to substitute for "simulations" (*à la* Sayre–Crosson) either the term "algorithmic models" or, as suggested by Sisson [30], the denominator "procedural models." Each of these terms carries a connotation, at least so among computer scientists, which would permit one to include certain algorithmic procedures, such as numerical integration techniques, as simulations. Some might argue, in those cases where the variable of integration is time, that such numerically analytic integration techniques indeed constitute a dynamic mimicry of the phenomenon described by the formalized differential equation. Again, the semantic difficulties of the term "simulation" become apparent. "Simulation" simply has come to mean different things to different people!

However, the essential distinction made by Sayre and Crosson needs to be emphasized. There does exist a class of symbolic models whose component symbols are not entirely manipulated by the operations of well-formed disciplines such as mathematics, mathematical logic, or numerical analysis. A few examples should suffice to illustrate the distinction which the author prefers to make by referring to the Sayre–Crosson "simulation" category as the class of *simular models*.

One of the oldest simular models is the static deterministic model for a cake (or other culinary delicacy): the housewife's recipe, an algorithmic model for the finished product, a model which certainly requires no mathematical operations. Another such simular model, though of the stochastic static variety, is a nonadaptive memoryless chess-playing program, which decides randomly among alternative, equally highly considered, moves. More interesting among simular models are the dynamic varieties such as the algorithm for determining the critical path in an acyclic connected graph (deterministic simulation) or the digital computer program describing the passenger-by-passenger activities of a bank of elevators subject to random demands (stochastic simulation).

A PROPOSED UNIFIED CATEGORIZATION OF MODELS

In summary, one is able to unify the previous efforts to classify models as follows. Basic cross-categorization schemes are the dynamic–static and the deterministic–stochastic, as defined in the preceding section. In addition, the third categorization criterion (that of Rosenblueth and Wiener) will also be retained, although their formal models will be henceforth referred to as symbolic models.

By reference to Table I, one sees that the following refinement of the material class of models is proposed: 1) *replicas*—spatial transformations of original physical objects in which the dimensionality of the modeled is retained in the replica; 2) *quasi-replicas*—physical models in which one or more of the dimensions of the modeled object is missing; and 3) *analogues*—physical models which bear no direct resemblance to the modeled phenomena, yet whose essential properties may be placed in a one-to-one correspondence with pertinent properties of the modeled.

At the extreme position of precision, then, among the material models are the replicas, for they incorporate the same materials (though perhaps dimensionally scaled or reduced) as does the original physical object. For example, a scale model of a riverine–estuarine system may not be scaled in depth commensurately with the scale reduction in the system's width and length, yet the presence of all three dimensions ensures that such a model be a replica. The most precise model, then, is the *duplicate*, such as presumably arises in manufacturing processes and in biological (identical) twinning.

Less precise among the material models are the quasi-replicas in which one or more dimensions of the modeled have been eliminated. Characteristic quasi-replicas are photographs, road maps, planetarium shows, cinemas, CRT displays of the performance of an endurance or flight test, and weather maps.

Considerably less realistic (though still quite useful) among the material models are those which replace the material representation or behavior of one physical object or system with that of another: the *analogue* model. In this

TABLE I
EXEMPLARY MODELS

		Material			Symbolic			
		Replication	Quasi-replica	Analogue	Descriptive	Simular	Formalization	
STATIC	Deterministic	Earthen Relief Map	Road Map	Statue of B. Franklin	Ten Commandments	Decision Logic Tables (See [33])	Ohm's Law	Increasing Generality
	Stochastic	Critical Dosage Test	Weather Map	Die Toss for Russian Roulette	Weather Report	Non-Adaptive, Random, Chess Playing Program	Equilibrium Queue Length	
DYNAMIC	Deterministic	Model Train Set	Planetarium Show	Analog Computer Circuitry for $\ddot{y} = -y$	Constitution of U.S.A.	Critical Path Algorithm	Lanchester's Laws	
	Stochastic	Drosophila Genetic Experiment	CRT Display of Endurance Test	White Noise Generator	Text on Darwinian Evolution	Vehicle-By-Vehicle Transportation Model	Stochastic Differential Equation	

Increasing Abstraction
Increasing Inferential Facility →
Decreasing Reality

regard, the aforementioned bronze statue of Benjamin Franklin becomes an *analogue* model (of the *deterministic static* variety), since Dr. Franklin was of flesh and bone, rather than copper and tin. Other analogue models include: the analog electronic computer "solution" for a time-dependent differential equation (*deterministic dynamic analogue* type); the use of a hybrid computer with shift-register random numbers so as to mime a stochastic time-dependent differential equation (see Korn [17] for details regarding this type of *stochastic dynamic analogue* model); and the throw of a single die with a black ace as a substitute for the revolver in a game of Russian roulette (a *stochastic static analogue* model).

Further removed from the physical objects, phenomena, and systems which one seeks to represent are the *symbolic (or literal) models*. Taking the cue of Black [1], the most general among symbolic models is the metaphorical or *descriptive* model. Such models, being expressed in terms of one of man's natural languages, are the most "natural" among symbolic models, but are subjected to manipulation and transformation only by means of the accepted rules of grammar. Exemplary descriptive models include: a twentieth-century text on Darwinian evolution (a *dynamic stochastic descriptive* model of life on the planet Earth); the *Constitution of the United States of America* (a *deterministic descriptive* model for social and political organization, the symbolic model's being of the *dynamic* variety due to its inclusion of an amending process); the Ten Commandments of Moses (a *static deterministic descriptive* model); and a weather report (a *static stochastic descriptive* model).

The use of natural language as a means of modeling is probably man's most elaborate (and perhaps most realistic) method of conveying a meaningful symbolic (nonmaterial) representation of a system or phenomenon. The descriptive model is a verbal (written) explanation of a process and is subject only to the rules of grammar applicable to the natural language in which it is expressed.

Somewhat more precise, though perhaps providing less reality in its representation, is the class of symbolic models defined, in the Sayre–Crosson sense, as simulations. Exemplary simular models have been discussed previously and are also provided for facile reference in Table I. These simular models may include grammatical structures (indeed, consider the typical simulation program written in an *ad hoc* simulation programming language), but may also incorporate mathematical expressions and formulas. In fact, one might speculate that the constitution for a republic such as that intended for the United States is quite nearly a simular type of model for social structure since most of its statements are clearly delineated procedures or constraints.

Finally, there remains the highly considered class of formalized models or *formalizations*: symbolic models that, in the Sayre–Crosson sense, consist of symbols which are manipulated entirely by the operations of a well-formed mathematical discipline such as the integral calculus, algebra, numerical analysis, or mathematical logic. Exemplary formalizations are also found cross-categorized in Table I.

CHOICES AND IMPLEMENTATIONS OF MODELS

A perusal of Table I reveals that, as one moves from left to right in the table, an increase in abstraction and a concomitant deviation from reality is encountered. The quasi-replica is a dimensionally reduced material model and therefore less representative of the original phenomenon than is a proper replication or duplicate. The analogue model provides a greater departure from reality in that it represents a *change of medium* from the modeled to the model. All the symbolic models require a similar change of medium from the physical phenomenon of interest to the written expression or model; many persons, especially those who have had significant training and experience in the use of analog computational devices, would feel that, of the two types of changes in modeling media, the analogue representation constitutes the less drastic alteration. (See e.g., Duhem [9, p. 70].) On the other hand, many competent writers and mathematicians might argue that natural language is the primary mechanism for conveying information, understanding, and culture among human beings, so that symbolic representations of systems and physical phenomena would in their minds be more realistic than the presumption of an arbitrary physical isomorphism (between model and modeled), which necessarily accompanies the analogue model.

As one moves from top to bottom among the entries in Table I, a transition to greater generality occurs. Clearly the dynamic model, whose attributes alter with time, is a generalization of the static variety, and, in each case, deterministic representations are merely special cases of stochastic models.

Consequently, in discussing the modeling process, one could well restrict his attention, without an attendant loss of generality, to the classes of dynamic stochastic models. The choice among the remaining categories becomes then an exemplary exercise in cost-effectiveness analysis. In general, the analyst faces a cost or time constraint within which inferences from the completed and validated model must be made. Accuracy requirements become additional constraints, often thereby eliminating from consideration many material models (which, though precise, are often inaccurate representations).

If the dynamic stochastic model is to be computerized, careful consideration should be given to the choice among the alternatives of analog, hybrid, or digital implementations. The temptation to employ the analog computer as an *ad hoc* analogue model is frequently overcome whenever the inevitable considerations of scaling and accuracy arise, and whenever one projects the time and costs of the reconstruction of physical circuitry during subsequent model verification, validation, and experimentation. On the other hand, many models capable of implementation on the electronic analog computer may be satisfactorily represented by mathematical formalizations which are solved by techniques of numerical analysis on digital computers. Indeed, a number of "digital–analog computer simulation languages" (see Brennan and Linebarger [4]) now exist to facilitate such transitions to digital machines. Frequently, the attendant decrease in concern regarding scaling, accuracy, stability, and model maintenance favors the transition, although the projected costs of developing the software program required by the digital implementation must be borne in mind.

Most symbolic models, unless of the descriptive variety, are capable of implementation on the digital computer, the machine designed indeed for symbol manipulation. Presuming then, that the system scientist wishes to represent a given system by a means other than by writing a treatise (or other descriptive model) depicting it, he is currently in a position to choose between the more abstract (and probably less realistic) formalized formulation and the less abstract (and perhaps more realistic) simular variety of model. In conjunction with the earlier comments regarding the two cross-categorization schemes, it would appear that *the dynamic stochastic model of the simular variety frequently provides just the appropriate balance of realism, ease of experimentation, cost of model maintenance, accuracy, and stability that one seeks.*

Indeed, the dynamic stochastic simular model is one of the most general modeling forms, since dynamic models include static representations as special cases, since stochastic models are generalizations of deterministic mimicries, and since simular models may include mathematical expressions of which the formalization is comprised exclusively. A number of *ad hoc* simulation programming languages have been recently developed (see, e.g., Tocher [32], Pritsker and Kiviat [25], Schriber [29], Kiviat *et al.* [16], Braddock and Dowling [3], and Blunden and Krasnow [2]), and the appearance of several texts on simulation methodology (see, e.g., Evans *et al.* [10], Martin [19], Mize and Cox [21], and Naylor *et al.* [22]) attests to the increasing recognition of the versatility of the dynamic stochastic simular model. In view of the apparently increasing unlikelihood of the existence and applicability of "scientific laws" to social, political, psychological, environmental, economic, and biological problems and phenomena, the less formal simular variety of model will, in all probability, increase in both popularity and stature.

STAGES IN A MODEL'S DEVELOPMENT

Of course, the intelligent selection of an appropriate model category and its method of implementation properly requires some *a priori* knowledge regarding the nature of the system to be modeled; and, since the actual construction of a model implies a prerequisite knowledge of the system, the decision regarding model type and implementation may frequently be deferred until adequate information regarding the system is available.

This deferment is usually quite practical in view of the fact that, regardless of the model type to be employed, the modeling process itself has been studied and dissected into its component parts. Contemporary operational philosophers such as Black [1] and Churchman [7] and management scientists such as Forrester [12] and Kiviat [15] have provided better and better descriptions of the modeling process. This orderly procedure for the construction of models is essentially equivalent, as we shall see, to the scientific method and is conducted in five pertinent stages, which are as follows.

1) Systems Analysis: This is the initial stage of a model's development, during which the salient components, interactions, relationships, and dynamic behavior mechanisms of a system are isolated.

2) System Synthesis: This describes that stage of a model's development during which the model of the system's behavior is organized in accordance with the findings of the preceding Systems Analysis stage.

3) Verification: The third stage of a model's development is that in which the model's responses are compared with those which would be anticipated *if indeed* the model's structure was prepared as intended.

4) *Validation:* This is that stage of a model's development during which the responses emanating from the verified model are compared with corresponding observations of, and measurements from, the actual system in order to establish the verisimilitude of the model and the modeled.

5) *Inference:* The final stage of a model's development is concerned with the definition of experiments with, and comparisons of responses from, the verified and validated model.

Prior to the actual commencement of the modeling activity, however, the systems analyst must ascertain the goals of his modeling effort. He must question the need for the model by enquiring of himself what analyses he would perform if indeed the model were at this time available for experimentation. Since the analyst will wish to conduct eventually such experimentation with a *credible* model, he will need to be concerned at the outset with the types of validation tests that he will be able to perform with the finished model; again, imagining himself in the context of actually possessing the completed model, the analyst should enquire both of the availability of the actual system for experimentation and of the likely comparisons (with the system) to which his model should be subjected.

This preliminary (or zeroth) stage of the model's development addresses the question, then, of appropriate *measures of system performance*. Consequently, the system's goal should be defined and understood quite early in the modeling effort. Of pertinence in this regard is the ability of the system scientist to project *himself* accurately as the system's "director" since in this capacity he will with greater facility understand the system, its goal, and the mechanism by which the system's components contribute to the achievement of the goal.

Of course, such a projection is not without its drawbacks, for the system scientist must often protect himself from the somewhat natural impulse to incorporate his own moral and value judgments in the model, thereby jeopardizing the objectivity required in providing an adequate accurate model of the system. (See Churchman [7] for a more complete discussion of the matter.)

Presuming then, that the system's goal and its performance measures are well understood by the analyst, the modeling process may properly commence. The initial (Systems Analysis) stage is concerned with the (usually abstract) breakdown, or analysis, of the system into its component entities. Immediately, the analyst is confronted with a decision regarding whether isolated aspects are properly intrinsic, or extrinsic, to the system's behavior. (We shall presume, without further ado, that the system under study evolves with time and that its model shall consequently be of the dynamic variety.)

Items deemed to be *outside* the system's intrinsic mechanisms are said to reside in the system's *environment*. A primary element of the System Analysis stage of a model's development, then, is the sorting of possible contributors to the system's behavior. The sorting is accomplished by exiling to the environment those elements which, though they may from time to time affect system entities significantly, are never affected significantly by any of the elements (entities) intrinsic to the system. Alternatively, any element which, though affected significantly by elements that are definitely intrinsic to the system, yet does not in turn affect internal system elements is also included in the system environment. Forrester [12] would apparently refer to this sorting process as the "search for the *feedback* structures that might produce the observed [systemic] behavior."

Thus primary goals of the Systems Analysis stage include: a delineation of those *entities* which interact with one another (often via decision loops or feedback processes) as the system strives to attain its goal; and the demarcation and definition of the *system boundary*, that conceptual artifice which separates the systemic entities from the environment.

As these goals are being accomplished, the systems analyst should be simultaneously occupied with the task of determining the necessary descriptors or *attributes* of the essential elements of the system. In this manner the *state variables* necessary to the description of the system's status at any point in time are tabulated. In this endeavor, the analyst will need to ascertain the mechanisms by which state variables change; this is accomplished by noting the conditions under which instantaneous *events* occur in the system, such as an increase in the number of waiting customers or the departure of a vehicle from a traffic node.

An event is thus characterized by an instantaneous change in one or more state variables. In many systems no discernable instantaneous events will be observed, such as is often the case for certain flow phenomena. If at the conclusion of the Systems Analysis stage, no such events have been isolated, then the attempt to construct an *event graph* (see Evans *et al.* [10] and Mihram [20]) will reveal that the model should be of the continuous type and, therefore, frequently capable of implementation on an analog computer (or, perhaps, as a formalized model implemented on a digital computer); otherwise, a discrete-type formulation, ideally suited to digital computer implementation, will likely be in order.

Of course, as the systems analyst conscientiously delves into the behavioral aspects and elements of a system, he finds that elements themselves become subsystems with their own behavioral characteristics. Reiterated application of conscientious investigation of the subsystem structures will likely lead to a great deal of incertitude regarding the system's elements and their interactive behavior. This uncertainty arises for several reasons, primary being the necessary constraint of the costs of extensive systems' analysis efforts and the fundamental limitations of the human observer. The resulting phenomenon, which the author refers to as the *Uncertainty Principle of Modeling*, provides an explanation of the frequent need for stochastic representations in meaningful models: "refinement in modeling eventuates a requirement for stochasticity." Consequently, the more conscientiously developed model will more likely be of the stochastic category.

Concomitant with the isolation of requirements for the stochastic elements of a system representation, the analyst will need to note elements of data that will be necessary to the structuring of an adequate model. Data requirements and the costs of data collection become important aspects of the system analyst's efforts to ascertain the relative cost-effectiveness of alternative formats for modeling the system under consideration. During the Systems Analysis stage then, a clear notion of the data requirements of the subsequent modeling effort should be formulated.

The initial stage of a model's development terminates with the delineation of the 1) system boundary, 2) system environment, 3) system entities, 4) entity attributes or system state variables, 5) the intrinsic feedback mechanisms or activities of the system, and 6) the events (if any) inherent in the system's behavioral structure. In addition, the need for stochastic events or representations in the model will have been revealed during the Systems Analysis stage.

The second stage (System Synthesis) of a model's development is concerned with structuring and implementing the model. Consequently, at the inception of this developmental stage, it is convenient to perform the cost-effectiveness analysis with respect to the selection of a model type and its method of implementation. Since we have already presumed the need for a dynamic model, the analyst is faced with a decision between deterministic and stochastic models, as well as between a material or symbolic representation (including a choice of one of their subcategories). In view of the Uncertainty Principle of Modeling, the first decision is often straightforward, though the incorporation of stochasticity for stochasticity's sake is clearly inadequate; whenever stochastic representations are indeed required, they should be entered into the model in accordance with appropriately applicable probability laws such as those of Poisson processes, the central limit theorem, and Bernoulli's theorem, as discussed by Feller [11], Parzen [24], and Mihram [20]. Methods by which stochastic elements may be generated in computerized models are discussed by Korn [17] and Chambers [5], among others.

The choice among the varieties of material and symbolic models is then made via comparisons of respective accuracies, implementation costs, data requirements, maintainabilities, and projected costs of the experimentation required in the subsequent three stages of a model's development. Educational costs associated with the learning of *ad hoc* simulation languages, if appropriate, must also be considered. For a more complete discussion, the reader is referred to Teichroew *et al.* [31].

Once the model has been synthesized, it is essential that the soundness of its structure, vis-à-vis that intended in the System Synthesis Stage, be ascertained. This Verification stage, for computerized models, consists of debugging and calibration tests which are designed to locate logical faults in the model's structure.

The completed dynamic model should, at the end of T time units, yield a response $R(T)$ which may be represented as a (generally unknown) function of the input, or environmental, conditions, which one may parameterize as a vector $(x_1, x_2, \cdots, x_p)$. The response becomes

$$R(T) = r_T(x_1, x_2, \cdots, x_p). \qquad (1)$$

In the case of stochastic models, the model's response becomes a random variable,

$$\begin{aligned} R(T) &= R_T(x_1, x_2, \cdots, x_p; S) \\ &= r_T(x_1, x_2, \cdots, x_p) + e(S) \qquad (2) \end{aligned}$$

where $r_T(x_1, x_2, \cdots, x_p)$ is a (generally unknown) response function, representing the *expected model response* at environmental specification $(x_1, x_2, \cdots, x_p)$, and where $e(S)$ is a random variable of mean zero, essentially a transformation of the randomly selected random number seed S, as required explicitly by most stochastic computerized models.

In the Verification of a deterministic model, it is thus imperative that the systems analyst be aware of some specific environmental condition, denoted by $(x_1^*, x_2^*, \cdots, x_p^*)$, for which the model response $R(T)$ could be exactly predicted if indeed the model's structure were as intended. One should note that verification tests are *not* conducted via comparisons of model responses with those of the actual modeled system; rather, comparisons between observed model responses and theoretically anticipated results are made in as many cases as possible for which a relationship of the form

$$R^*(T) = R(x_1^*, x_2^*, \cdots, x_p^*)$$

is known.

For stochastic models, Verification tests require statistical procedures. If there exists a specific environmental condition $(x_1^*, x_2^*, \cdots, x_p^*)$ for which certain statistical properties of the random variable

$$R^*(T) = r(x_1^*, x_2^*, \cdots, x_p^*) + e(S)$$

are known, then the observation of the responses from k "independently and randomly seeded" iterations or *encounters* of the model will correspond to the collection of a random sample of R^* values; in the standard statistical manner the one-sample test of the hypothesis that, say, the mean simular response is

$$r(x_1^*, x_2^*, \cdots, x_p^*) = r_0$$

corresponds to a Verification test for the model.

One should note that a Verification test for a stochastic computerized model may fail, even though the model be properly structured. This is typical of scientific investigations in which both Type I and Type II statistical errors must be acknowledged. In a sense, Verification tests of the stochastic model may be construed also as tests of the model's random number generator; therefore, separate tests of the generator should be undertaken to avoid confounding the Verification test aims.

The calibration tests of the Verification stage of a model's development serve as a check on the System Synthesis stage. Before a model can be generally deemed credible, similar

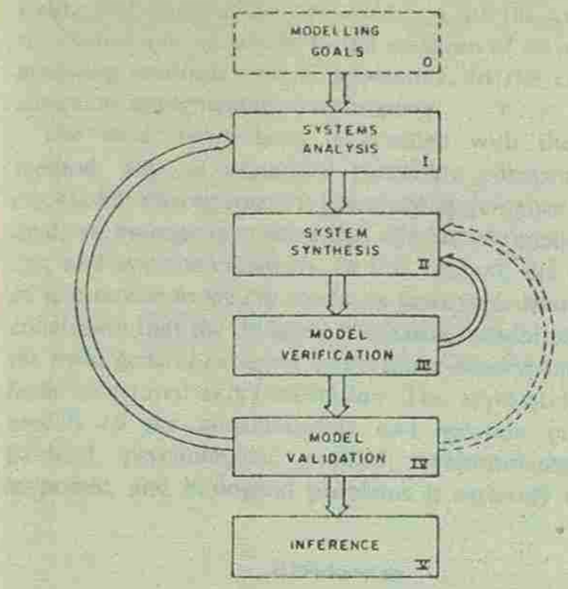

Fig. 1. Modeling process.

checks on the original Systems Analysis stage would be required. The Validation stage of a model is undertaken with this goal in mind and is accomplished by comparisons of responses from the (now verified) model with corresponding responses or measurements recorded from the actual (modeled) system.

Experimentation is thus conducted both with the model and with the modeled system. Whenever the modeled system is not available for such experimentation, proper validation tests will not be feasible, implying that the analyst undertakes a greater risk in making any subsequent inferences regarding the modeled system from comparisons of model responses.

Presuming that Validation tests can be undertaken, the systems analyst fixes the operating conditions for the actual system and, after T time units, records the resulting system performance. Then, setting the corresponding environmental conditions for the model, responses are recorded after the appropriate comparable amount of time and are compared on essentially a one-to-one basis with those of the actual system. In this context, the established procedures of system identification (see Sage and Melsa [34]) are appropriate to model validation. The validity of formalized stochastic models is also of considerable concern currently to statisticians. (See the comments and rejoinder adjoining the enlightening discussion of Efron [35].)

Whenever the model is deterministic, this comparison is quite straightforward. Discrepancies imply an inadequate or improperly conducted Systems Analysis stage, frequently due to a failure to have heeded the Uncertainty Principle of Modeling. In these cases, a revised Systems Analysis must be undertaken and a return through the System Synthesis and verification stages will likely be in order before Validation tests can be again undertaken. (See Fig. 1.)

If the model is stochastic, model validation becomes, like model verification, a statistical procedure. However, since in this case two random samples (one of model responses, the other of system observations) will need to be compared, typical validation tests become two-sample tests for equality of means or, say, homogeneity of variance. (See Mihram [36].)

Again, the failure of any statistical *validation* test implies the need to return to the initial stage of a model's development. Any failures of subsequent *Verification* tests require returns to the second or system Synthesis Stage for rectification of the model structure. Such cycling through the stages of a model's development is quite typical (though it is preferably held to a minimum), and it is quite common to most scientific enquiry. In a sense, the five developmental stages are essentially modeling "thresholds," although the attainment of any higher level threshold does not imply the impossibility of a return to a lower level subsequently.

In the final stage (inference or model analysis) of a model's development, experiments are conducted with the verified validated model solely. There are three general categories into which most analytical modeling goals or aims can be placed: 1) the determination of the *dynamic behavior* of the model during a stipulated period T of time; 2) the determination of the relative (or marginal) effects of unit changes in each of the environmental conditions $(x_i, i = 1,2,\cdots,p)$ on the model's expected response at the end of a specified period T of time; and 3) the determination of the particular environmental specification $(x_1', x_2', \cdots, x_p')$ at which the model's expected response ($R(T)$ of (1) or $r_T(x_1, x_2, \cdots, x_p)$ of (2)) is optimized.

The methodologies for achieving these modeling goals depend upon whether the model is deterministic or stochastic; typical methods are tabulated in Table II. For many of the statistical procedures, the reader is referred to Cochran and Cox [8] or Mihram [20].

TABLE II
METHODOLOGIES FOR MODEL ANALYSIS

Analytical Goal	Model Category	
	Deterministic	Stochastic
(1) Dynamic Effects	Fourier analysis Polynomial curve fitting	Tintner's Technique Autocorrelogram Spectral analysis
(2) Marginal Effects	Discounted Cost-Effectiveness Comparisons	Factorial Experimental Designs Regression Analysis (Analysis of Variance and Covariance) Multiple Rank Tests
(3) Optimal Conditions	Optimum-seeking methods	Response Surface Methodology Stochastic Approximation

SUMMARY

This paper presents a taxonomy of models discussed in the context of scientific enquiry. Twenty-four cross-categorized model types are defined, and examples of each are given. One might note that hybrid combination of the types are possible; e.g., contemporary operational gaming consists of a computerized simular model, a set of playing rules (descriptive), and human participants (physical replicas). The choice among model types for particular applica-

Fig. 1. Modeling process.

tions is presented as a cost-effectiveness study in its own right, and suggestions are made as to the criteria and the evaluations necessary to the selection of an appropriate modeling medium and, if applicable, to the choice of a computer implementation alternative.

The modeling process is equated with the scientific method, and an organized procedure consisting of five essential modeling stages is presented as guidance to systems analysts, management scientists, operations research specialists, and systems engineers. In this context, the evaluation of alternative modeling media is discussed, leading to the conclusion that the dynamic stochastic simulation model is the most general category of symbolic models that permits facile structured experimentation. The application of such models to the understanding and solution of societal, political, psychological, judicial, environmental, social, economic, and biological problems is certainly imminent.

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[illegible] is presented as a cost-effectiveness study [illegible], and suppositions are made as to the [illegible] and the evaluations necessary to the selection of an appropriate modeling medium and, if applicable, to the [illegible] of a computer implementation alternative.

The modeling process is related with the scientific method, and an organized procedure [illegible] of five essential modeling stages is presented [illegible] analysts, management scientists, [illegible], and systems engineers. In this context, the evaluation of alternative modeling media is discussed, leading to the conclusion that the dynamic stochastic [illegible] the most general category of symbolic models that [illegible] structural experimentation. The [illegible] models to the understanding and solution [illegible] political, psychological, judicial, [illegible] economic, and biological problems is [illegible]

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Energy/Futurology

Satellite power stations: a new source of energy?

Solar cell power, converted to microwave power, is beamed to earth and reconverted

William C. Brown Raytheon Company

The rapidly increasing demand for electric energy[1,2]—coupled with the inability of conventional means of electric power generation to keep up with that demand—makes urgent the need for new prime energy sources for future electric power generation. In addition to nuclear fuels, there are many potential sources of energy that are not now being used in appreciable amounts: wind and tidal energy, geothermal energy, temperature differences in the ocean, and solar energy. This article will be concerned with solar energy.

For each possible energy source, including nuclear fission and fusion, there is some factor that limits the degree of optimism. Either the source is too small to qualify as a major energy source, hard-to-assess pollution and ecological hazards are unavoidable, the technology has not yet been reduced to practice, or there is an economy barrier. Solar energy falls into the last category.

The amount of solar energy intercepted by the earth is at least 10 000 times the projected consumption of electric energy in the year 2000. Because the sun's energy has such a low density at the earth's surface, any earth-bound power generation scheme based on the sun as energy source would require relatively large areas devoted to devices that either convert the sun's energy directly into electricity or function as boilers for a system employing turbogenerators. Moreover, the day-night cycle, atmospheric attenuation, cloud coverage, and other factors reduce the amount of solar energy falling on a given location to a small fraction of that falling on the same area in space. In December, for example, the sunniest locations in the United States, located in the Southwest and in Florida, receive only 11 percent of the energy that a similar area in space would receive.[3] In New York and Seattle, by contrast, the percentages would be 4.5 and 2.2 respectively. The impractical result of these poor duty cycles is an excessive investment in solar energy devices[4] to capture a given amount of energy. And an equally excessive investment in storage facilities must be made if the captured energy is to be used as a reliable base-load source of electric power.

To overcome the problems resulting from this poor duty cycle, Dr. Peter Glaser of Arthur D. Little, Inc., proposed, in 1968, that we put large arrays of solar photovoltaic cells into space in near-equatorial synchronous orbit where the sun would shine upon them nearly 100 percent of the time.[5] The dc power obtained from the photovoltaic arrays would then be converted into microwave power, beamed to the surface of the earth, and there converted back into dc power. Because the rotation of the solar satellite would be synchronous with that of the earth, the microwave link would be fixed and operative at all times. This concept has become known as the Satellite Solar Power Station (SSPS).

Dr. Glaser's proposal was received with considerable interest because of the concept's inherently low thermal pollution; because of the absence of any form of particulate, chemical, or nuclear pollution; and because of its association with a dependable, inexhaustible source of energy—the sun. This interest has led to a series of studies of the technology and associated economics of the system in stages of increasing depth.[5-7] The latest study was performed by a four-company team, with Dr. Glaser as its leader, consisting of personnel from A. D. Little, Inc., the Grumman Aerospace Corp., Raytheon Co., and Textron, Inc.

After a six-month study of all aspects of the SSPS, the team reached the conclusion that the satellite solar power station concept, as proposed by Dr. Glaser, is technically feasible.[7,8] The present cost projection—based upon solar cell costs derived from an automated version of today's conventional silicon solar-cell technology and upon space transportation costs as represented by a first-generation space shuttle—is too high to be cost competitive with established methods of power generation. Because of the 15 to 25 years projected time frame for the SSPS to become operational, it is entirely possible that breakthroughs in cost will occur.

A preferred way to view the SSPS system concept is that it is a pollution-free, resource-conserving approach to the solution of our energy problem in the time frame 1990–2000 and that it is based upon an inexhaustible prime energy source, our sun. Although not currently cost competitive, it is an option that should be considered carefully and kept open in the event cost breakthroughs occur and unexpectedly severe problems arise in the development of other approaches.

System configuration and characteristics

The overall configuration and principal characteristics of the SSPS to be presented make up a "baseline" design.[7] It is not intended as a final design but rather to serve as a starting point for further study and the evolution of improved designs.

The system is shown on the front cover of this issue. The SSPS is placed in an equatorial, synchronous geocentric orbit 35 800 km above the earth's equator so that its position with respect to any other position on the earth's surface is fixed. Two large solar photovoltaic cell arrays, always pointed toward the sun, convert the sun's radiant energy to dc power, which is then transferred to a large, active phased array mounted by means of two rotary joints between the two solar arrays. The active phased arrays' functions are to convert the dc power into microwave energy at a preferred wavelength that will penetrate the earth's atmosphere and to focus that energy into a narrow beam pointed toward the receiving point on the earth's surface.

The microwave beam in space is unattenuated and arrives at the earth's atmosphere with the same power level as at launch. The microwave energy then penetrates the earth's atmosphere and reaches the earth's surface where it is efficiently converted back into dc power by a device known as a "rectenna," which simultaneously absorbs and rectifies the incoming microwave energy.

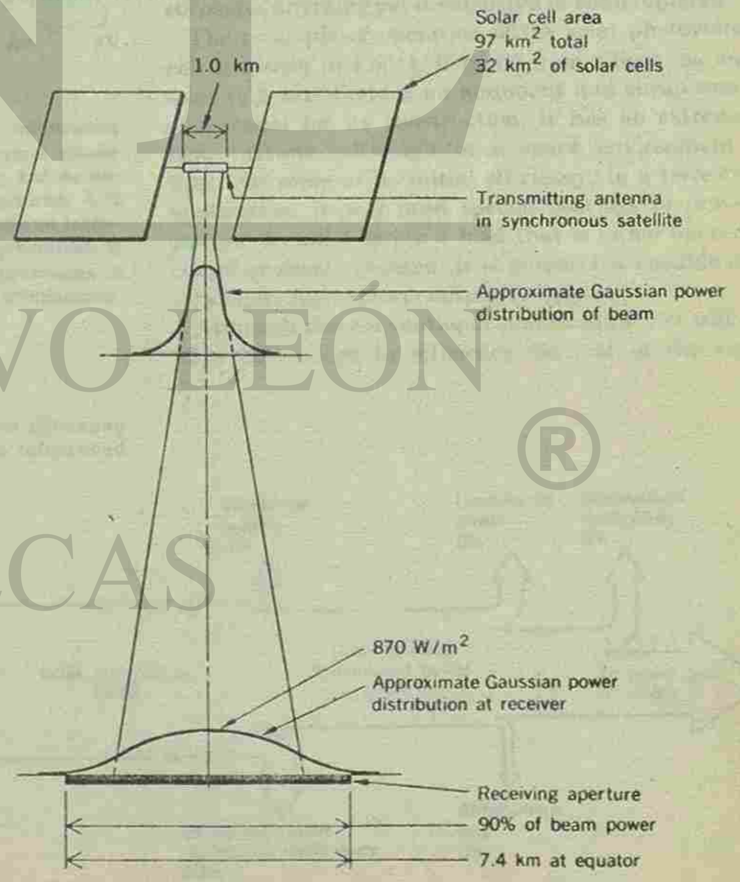
An important characteristic of the SSPS system is its high duty cycle. Because of the 23-degree tilt of the earth's axis with respect to the ecliptic plane, and the fact that the satellite is at a distance of 35 800 km (22 400 miles) from the earth in equatorial orbit, the SSPS is continuously illuminated during the winter and summer months and well into the spring and fall months. For 22 days before and after the vernal and autumnal equinoxes the satellite is eclipsed for periods of time ranging up to a maximum of one hour and 14 minutes. If the satellite and ground rectenna are located at the same longitude, the eclipse period will center around midnight. The average duty cycle for the entire year is slightly more than 99 percent.

The proposed electrical size of a single SSPS is in the range of 3000 to 15 000 MW. To place this power level in perspective, 10 000 MW represents about 3 percent of the electric generating capacity in the United States today but only 0.5 percent of the projected capability in the year 2000. The electrical size of the system is determined primarily by the power level at which the construction cost per kilowatt of output is at a minimum. Although many parameters are involved, the most important ones appear to be the area of the transmitting antenna aperture required for efficient transmission of power, the most efficient utilization of this area for radiation of waste heat, and the bus losses associated with the transmission of dc power from the solar cell array to the transmitting antenna.

The choice of frequency for the microwave transmission of power, from a strictly technological point of view, involves several factors: how the attenuation and scattering of electromagnetic energy in the earth's atmosphere behave as a function of the wavelength of the energy; the physical size of the transmitting antenna and receiving rectenna; and the efficiency of the components that interchange dc and microwave energy. A study of atmospheric attenuation versus wavelength shows that a wavelength of 7.5 cm (4 GHz) or longer is necessary to avoid excessive attenuation (>1 dB) during a heavy rainstorm, the form of atmospheric disturbance having greatest impact upon microwave propagation. Atmospheric scattering and attenuation effects become much more pronounced at millimeter and optical wavelengths and prevent serious consideration of this part of the spectrum for efficient power transmission.

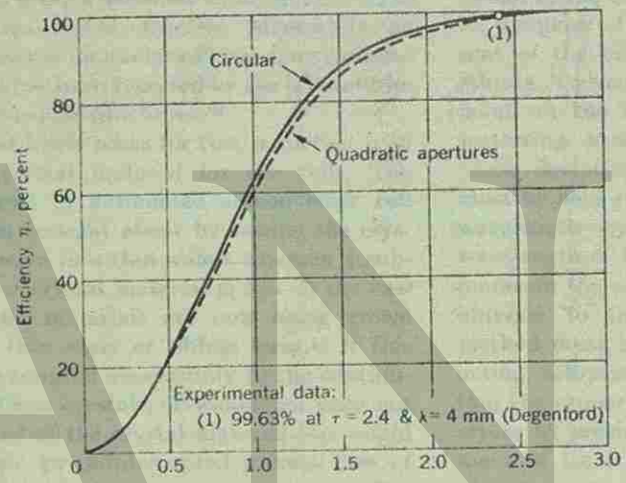
From the viewpoint of keeping aperture sizes small, a short wavelength is preferred since the total area of the two apertures is proportional to wavelength for a given efficiency. However, substantial aperture areas are necessary for disposal of any waste heat resulting from any inefficiencies in energy conversion, particularly in space. Energy conversion components presently have better efficiency at the longer wavelengths.

[1] Dimensions of essential physical features of the SSPS for a 10 000-MW system.



The net result of these considerations is that at the present time, and from a strictly technological point of view, the best compromise appears to be in the relatively narrow range of 7.5 to 15 cm. In the SSPS design, a wavelength of 10 cm has been assumed.

The proposed physical size of the present base-line design is shown in Fig. 1 for a 10 000-MW system. The solar energy collecting array has an area of 97 km^2; one third of that area is made up of solar cells and the remaining area consists of inexpensive solar concentrators made from thin-film material treated to have a reflecting surface. The transmitting antenna is 1 km in diameter, and the rectenna array to capture 90 percent of the transmitted energy is 7.44 km in diameter. The antenna dimensions are derived from the relationship between efficiency and physical parameters given in Fig. 2.



[2] Theoretical transmission efficiency for a microwave beam radiated from an aperture with a spherical phase front whose radius is equal to the distance D. A_t and A_r are the areas of the transmitting and receiving apertures, λ is radiation wavelength, and D is the distance between transmitting and receiving apertures. Aperture illumination is unique for each value of efficiency but approximates a slightly truncated Gaussian distribution for high efficiencies. One point of experimental data is given.

The overall efficiency of the SSPS system is the product of the efficiency of the solar cell array and the microwave power transmission system. The solar cell conversion efficiency is limited, primarily because of the distribution of the sun's energy over a very broad frequency spectrum. The conversion efficiency of today's silicon solar cells is in the range of 12 percent. It is expected to improve to 18 percent[9] but never to exceed 25 percent. The use of concentrators reduces the cost and weight of the array but the resulting higher temperature of the cell also reduces the projected efficiency of the solar cell to 11.5 percent.[7]

By contrast, the overall efficiency of the microwave power transmission system is projected to be in the 65 to 70 percent range. Figure 3 shows the various power flows and losses in the SSPS system using the dc power input to the active phased array as the 100 percent reference point.

The specific weight of the satellite portion of the SSPS system, important because of space transportation costs, has been estimated to be 2.5 kg/kW of output.[7] More than half of this weight is associated with the solar cell array.

The satellite solar power station would be placed into orbit with the space shuttle[7] or perhaps a second-generation shuttle that would transport material from the earth's surface to near-earth orbit and a space tug utilizing high-specific-impulse electric propulsion to go from near-earth to synchronous orbit.

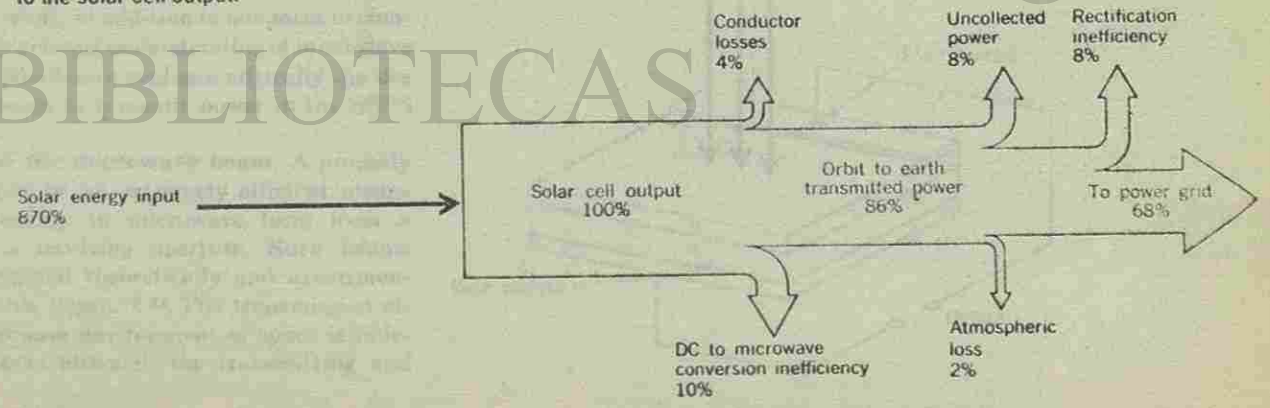
Solar photovoltaic cell array

In the SSPS the sun's energy is converted into electric power by a large photovoltaic array optimized for this purpose. Its design uses construction techniques extrapolated from present practices but the scale far surpasses anything yet constructed or contemplated.

The principle of operation of the solar photovoltaic cell is shown in Fig. 4. If made from silicon, as most solar cells are, there is an abundant and cheap source of material for its construction. It has an extremely long lifetime, although in a space environment it may lose some of its initial efficiency. In a terrestrial application, it will need special coatings to prevent erosion. It will tolerate a load that is either open-circuited or short-circuited. It is potentially capable of a very high ratio of power output to weight.

Although the conventional photovoltaic cell will always be limited in efficiency because of the sun's

[3] Projected flow of power in the SSPS system indicating various losses. The power flows and losses are referenced to the solar cell output.



broad spectrum of energy, an efficiency of 18 percent reportedly achieved with a cell based on gallium arsenide[10] represents about half the efficiency of conventional or nuclear generating plants using fossil or nuclear fuels. Solar cells also have the advantages that their prime source of energy, the sun, is inexhaustible and cost-free and that there are no residual wastes to dispose of.

The solar cell, in spite of its advantages, has not moved into serious contention as a source of large amounts of electric power because of its relatively high cost and poor duty cycle when terrestrially based. In space, however, it has been used widely and now represents the major source of power for satellites that are required to operate reliably for long periods.

As the result of the growing concern over future energy sources, there has been a renewed interest in improving the solar photovoltaic cell in terms of efficiency and reduced manufacturing cost. A recent study sponsored by the National Academy of Sciences[9] has indicated that an increase in efficiency of the silicon solar cell from its present nominal value of 12 to 18 or 20 percent is a reasonable objective. Meanwhile, an efficiency of 18 percent for a solar cell based on gallium-arsenide material has been reported by the laboratories of International Business Machines.[10]

One of the most likely areas for cost reduction is in growing silicon crystal material for the cells. The chief projected cost of automated silicon solar cell production is that brought about by sawing the crystal material as grown into thin wafers whereby a substantial amount of crystal material is lost in the saw kerf. Some crystal materials are now being grown commercially in thin sheet or ribbon form.[11] If this method could be adapted successfully to the continuous growth of silicon crystals, it would not only cut drastically the cost of the crystal material but would also make possible an uninterrupted process flow of the silicon material from the molten state to the finished silicon solar cell.[12] A resultant cost of $375 per kilowatt has been projected from a study[13] based upon an assumed successful adaptation of the ribbon process to silicon solar cells.

Microwave power transmission system

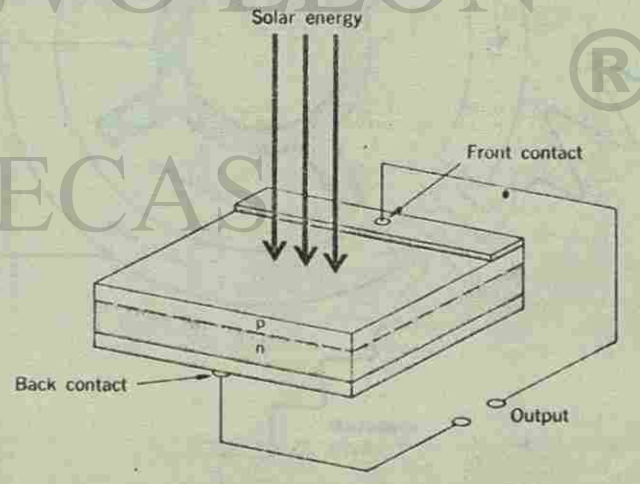
The proposed use[5-14] of a microwave beam for efficient transfer of large amounts of power over long distances is a radical departure from the traditional use of microwaves in radar and communications. A considerable amount of effort in the experimental development of microwave power transmission systems has been supported by private and Government agencies[15-18] and this effort, in addition to advances in component technology and our understanding of microwave beams, makes it possible to evaluate critically the use of a microwave beam to transmit power in the SSPS system.

The forming of the microwave beam. A properly launched beam can be an extremely efficient means of transporting energy in microwave form from a transmitting to a receiving aperture. Such beams have been investigated theoretically and experimentally in considerable depth.[19-22] The transmission efficiency in the vacuum environment of space is independent of distance, although the transmitting and aperture areas must increase in proportion to the distance. The relationship between efficiency η, transmitting and receiving apertures A_t and A_r, transmission distance D, and the wavelength λ of the radiation is shown in Fig. 2.[19] One experimental data point of 99.6 percent[22] is shown in Fig. 2.

The application of Fig. 2 to the problem of transferring power from a synchronous satellite over a distance of 35 800 km using a radiation wavelength of 10 cm shows that for 90 percent power transfer efficiency the product of the receiving and transmitting apertures must be 34.1 km^4. If the transmitting aperture is 1 km in diameter, then the receiving aperture will be 7.44 km in diameter, as shown in Fig. 1. The relationship provided by Fig. 2 requires that for each value of efficiency there must be a specific distribution of illumination at the transmitting antenna. For high efficiency values, this illumination approaches a slightly truncated Gaussian.

The gain of the transmitting antenna will be very high, of the order of 90 dB for the present base-line design of the SSPS transmitter. The proposed rectenna diameter of 7.44 km required to intercept 90 percent of the beam represents an arc segment of 0.7 minute. To maintain a given spot size around a given point on the earth's surface, and to maintain low scattering losses from the transmitting antenna, phase deviations over the phase front of the beam must be held at launch to within a small fraction of a wavelength—typically within 5 mm for a transmitted wavelength of 10 cm. Since it would be impossible to maintain the physical alignment of the surface of the antenna to this tolerance, some beam launching method must be employed that uses one of the fast-acting, self-phasing concepts.[23] These methods maintain the proper phase over the entire transmitting aperture by sensing electronically the physical displacement of local areas and compensating for any displacement by changing the phase of the microwave radiation at the point of launch. To be effective in the

[4] Salient features of standard solar cell. Basic material is single-crystal, n-type silicon. Thin layer of p-type material is formed on one surface. Enough energy is transferred from the incoming solar rays to the holes and electrons in the silicon to overcome the junction barrier voltage and to establish current flow in the external circuit.



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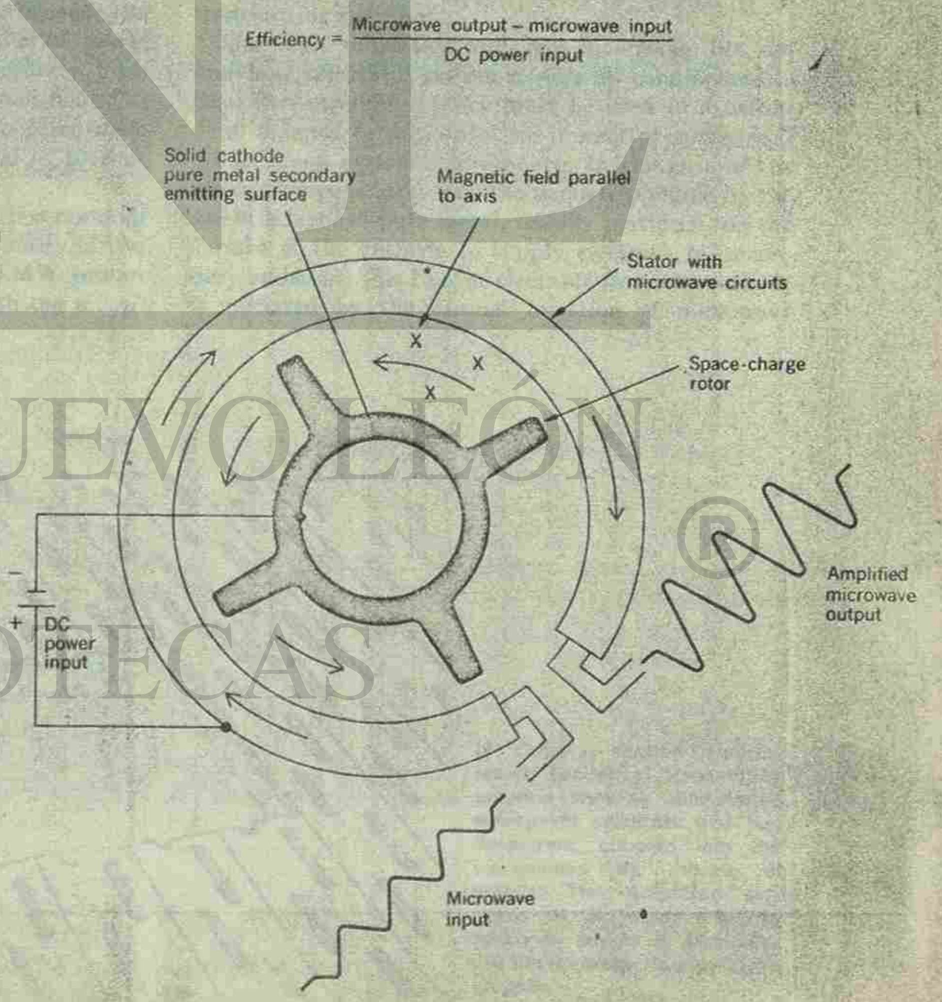
SSPS, these self-phasing concepts would require that the transmitting antenna be subdivided into a large number of smaller arrays so that the phase of the radiated output from each subarray could be controlled independently. The reference phase front, with which the output phase of each subarray is compared, would be established by an independent transmitter located on earth at the center of the receiving location for the power beam.

The overall efficiency of a microwave power transmission system depends upon the conversion efficiencies at both ends of the system as well as upon the launching and beam efficiencies. Conversion devices have already exhibited highly efficient operation and even greater efficiencies are possible if advantage is taken in device design of newly available materials.

Conversion of dc to microwave power. In the SSPS system, the space environment imposes unusually severe requirements upon the conversion of dc power to microwave power. Waste heat disposal, the need for extremely long life and high reliability, and the demand for light weight assume an importance far above that encountered in a terrestrial environment. In the base-line design, one promising device, the crossed-field electron tube, was selected for examination to see how well it would meet the stringent requirements if integrated into the overall system. It will not necessarily be the final choice.

The crossed-field device is the most efficient converter of dc power to microwave power in the wavelength range of interest. In both its oscillator form (magnetron) and amplifier form (Amplitron) it has exhibited overall conversion efficiencies of between 85 and 90 percent.[24] With the aid of the recently developed permanent magnet material, samarium cobalt, the device can also be made very light in weight.

In both the magnetron and the Amplitron, as shown schematically in Fig. 5 for the Amplitron, there is a rotor consisting of spokes of space charge that induce high-frequency alternating currents in a stator composed of a microwave circuit. The electric fields from the energy in the microwave circuit, in turn, exert a force against the spokes of space charge. The torque required to spin the rotor comes not from external mechanical torque, as in the 60-Hz alternator, but from the motion of charged particles in static electric and magnetic fields oriented at right angles to each other. Unlike the mechanical rotor of the alternator, the space-charge rotor of the crossed-field device has very little mass and rotates at extremely high speed—perhaps 100 000 000 times that of a 60-Hz alternator. Since the power generated by any device is



[5] Principle of operation of the Amplitron. Rotating spokes of space charge induce currents into the microwave circuit and provide efficient amplification of the microwave input signal. DC to microwave conversion efficiencies of over 85 percent have been obtained from the cross-field device.

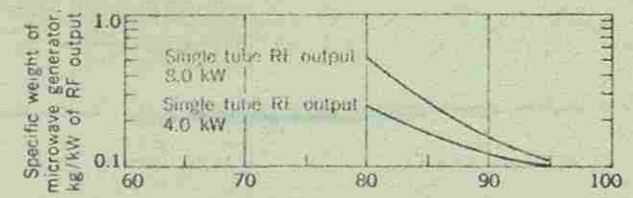
proportional to the product of torque and angular velocity, the capability of the small, lightweight microwave device to generate large amounts of microwave power becomes evident. This inherently lightweight mechanism, in normal practice, is highly disguised in conventional tubes because of the mass of the magnet required for operation and the mass of the glass and metal envelope required in the terrestrial environment. In space, the envelope is not required and the new samarium-cobalt magnet material can reduce the magnet weight by a factor of at least ten.

In the SSPS system, the power-handling capability of the device and its weight are directly related to disposal of the waste heat that results from any inefficiency in operation. Weight and reliability considerations require that waste heat be disposed of by direct radiation into space so the generator must have an efficient radiator fin attached to it. Fortunately, the large area of the transmitting antenna allows these radiators to dispose of a large amount of waste energy if the generators are uniformly distributed over the antenna's area. At 300°C, for example, a disk 1 km in diameter has a black-body radiation capability of 4.46×10^6 kW from each of its faces.

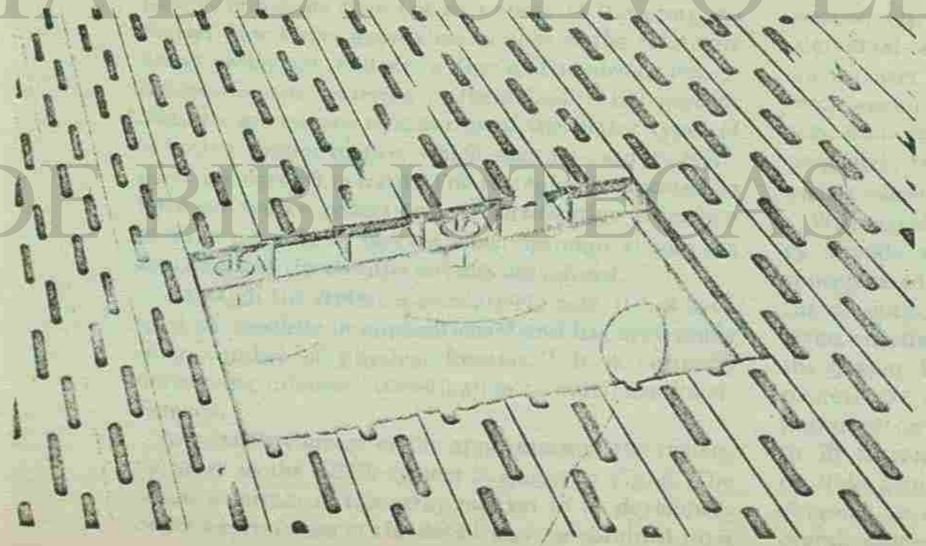
A study has been made of the specific weight of the crossed-field generator together with its permanent magnet and its pyrolytic graphite radiator as a function of Amplitron efficiency and power-handling capability. The results are given in Fig. 6. The specific weight of the combined generator and cooling fin, as measured in kg/kW of output power, is sensitive to both efficiency and power level primarily because the weight of the cooling fin approximates the 2.5 power of the quantity of waste heat it must radiate. This consideration places a practical upper power bound of about 10 kW on the microwave generator. Microwave tubes with power ratings that are nominal by present standards would be used in the SSPS.

Use of microwave power amplifiers with a nominal power rating of 5 kW would require a quantity of two million such tubes to produce a 10 000-MW microwave beam. The problems associated with the microwave excitation of such a large number of tubes, and the efficient coupling of them into a phased array, are resolved by a cascade arrangement of tubes and slotted waveguides, as suggested by the artist's rendering in Fig. 7. The output of each Amplitron flows into a section of slotted waveguide where most of the power is coherently radiated and becomes part of the microwave beam. Enough power is left over to excite the next Amplitron. The cycle is then repeated for the next section of waveguide and the next Amplitron, etc. Not within the scope of this discussion are the methods of phase correction and other controls that integrate the cascaded arrangement into the antenna subarray and insure proper overall behavior of the transmitting antenna.

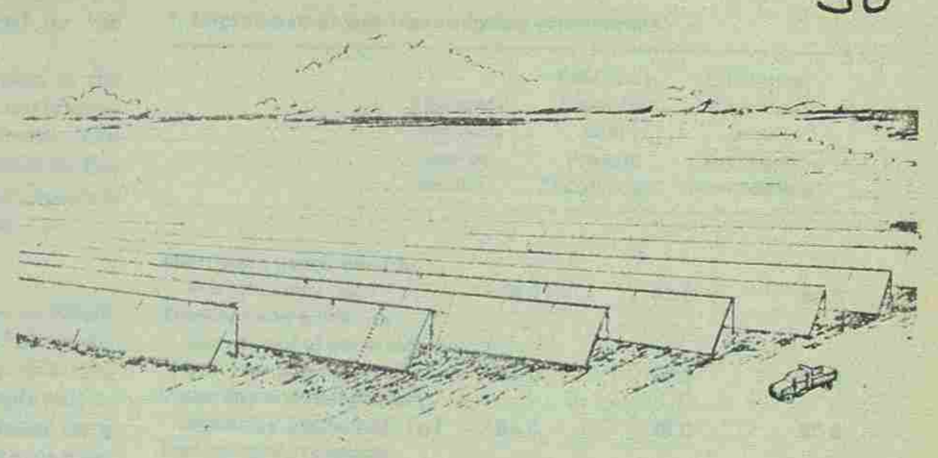
The high reliability and long operating life demands of the SSPS system require all components to have this capability. They must be used in a redundant manner to minimize the impact of component failure upon system performance. In the case of the microwave generator, long life is made possible by the use of a layer of pure metal, usually platinum, on the surface of the cathode to supply electrons by secondary emission. The flow of electrons from the cathode is initiated by the normal injection of microwave



[6] Specific weight of microwave generator and associated magnet and cooling radiator as a function of generator efficiency and power rating of tube. Radiation from both sides. Average fin temperature is 300°C, temperature rise in fin is 50°C, temperature of tube edge is 325°C, radiator material is pyrolytic graphite, and heat sink is space 0°K.



[7] Cutaway section in earth-facing section of transmitting antenna showing the slotted waveguide radiators and two Amplitrons coupled into the waveguides by means of probes. The Amplitron disposes of its waste heat to space by means of a circular cooling fin made from pyrolytic graphite.



[8] Artist's sketch of the SSPS rectenna, the electronic device that captures the energy from the microwave beam and simultaneously converts it into dc power for distribution on a conventional power grid. The rectenna need not be accurately pointed toward the transmitting antenna for efficient operation and its operation is independent of any distortion of the microwave beam as it passes through the earth's atmosphere.

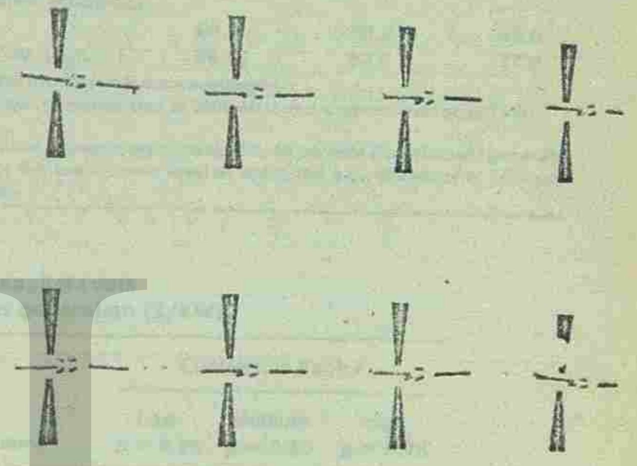
energy (see Fig. 5) into the microwave input terminal of the tube so that no initiation of electron flow by thermal means is needed. This technique eliminates the need for a cathode heater that not only has a limited life but, in this application, would impose an additional complication because of its separate power supply requirement. There is no known life limitation to the secondary emission process from a pure metal cathode other than erosion from sputtering, and this is expected to be negligible in the high vacuum of space. The use of pure metal cathodes, and starting them with RF injection, is a standard procedure in many terrestrial applications.

The efficient capture and rectification of the microwave power over such a large receiving area would probably not be practical if it were not possible to combine these two functions in the rectenna[25] and thereby simultaneously achieve high collection and rectification efficiency, insensitivity of the array to amplitude and phase perturbations of the incoming beam caused by atmospheric phenomena, insensitivity to the direction of the incoming radiation over a considerable angle, economical construction, and disposal of waste heat by passive radiation.

Structurally, the rectenna consists of many independent receiving elements, each of which is terminated in a rectifier. The dc outputs of the rectifiers feed into a common load. If the receiving element is a half-wave dipole, then the directivity of the array, no matter how large, approximates that of the relatively broad-patterned, half-wave dipole. The absorption efficiency of the rectenna is theoretically 100 percent and the microwave efficiencies of the better types of Schottky-barrier diodes, which may be used as rectifiers, are over 80 percent. The rectenna is expected to have an overall collection and rectification efficiency of 85 or possibly 90 percent when optimum diodes are designed and the rectifier circuits are refined.

Although the rectenna is relatively new, it has been used successfully in applications[26] and has been made in a number of physical formats.[27] It is currently undergoing intensive investigation to maximize its efficiency.

An artist's concept of the appearance of the rectenna array in the SSPS system is shown in Fig. 8. The detailed format of the array has yet to be developed. Some appreciation of the detail may be obtained from a laboratory model of the rectenna shown in Fig. 9. Printed circuit techniques would undoubtedly be used in production designs.



[9] Laboratory model rectenna made of elements consisting of a half-wave dipole and solid-state rectifiers. Elements are mounted in a plane one quarter wavelength above a reflecting metal surface. Overall capture and rectification efficiency, experimentally achieved, is 63 percent. Potential overall efficiency is 85 to 90 percent.

Microwave power transmission efficiency

The overall efficiency of a microwave power transmission system is defined as the product of the three individual efficiencies associated with dc-to-microwave power conversion, microwave transmission, and microwave-to-dc power conversion. In the SSPS system, an overall efficiency of 65 to 70 percent has been projected. How does this compare with various efficiency measurements in the laboratory?

With excellent dc-to-microwave conversion efficiency already well established,[24] laboratory effort has concentrated on output of the microwave generator to the dc output of the rectenna. Recent results[18] have given an efficiency of 60.2 percent for this portion of the system. Recent improvements in rectenna design, making use of improved Schottky-barrier diodes and improved rectifier circuits, will soon raise this figure to 70 percent. If this efficiency is multiplied by a credible generator efficiency of 85 percent, already obtained in some magnetrons and Amplitrons,[24] an overall efficiency of 59 percent is obtained, which is approaching the 65 to 70 percent projected for the SSPS.

The achieved efficiencies and those expected in the future are given in Table I. It shows an eventual laboratory overall dc-to-dc efficiency of 77 percent. The principal reason for this high efficiency is that in the laboratory nearly all of the beam can be intercepted whereas in practice this may be uneconomical.

Projected costs for the SSPS system

Table II gives the estimated capital costs of SSPS power generation in dollars per kilowatt.[8] Various confidence levels are reflected in the three different estimates of total cost and principal-components cost.

The estimates for the solar array were based on a straightforward extrapolation of existing manufacturing techniques into a highly automated format justified by the huge production volume. They did not take into account possible breakthroughs in manufacturing techniques, such as those already discussed.

The cost for the microwave transmitting antenna (designated "microwave" in Table II) and the rectenna were arrived at by a consideration of the basic materials involved and a highly automated production line, again justified by the huge number of identical units to be produced. The cost of the microwave generators was based on the very low cost of already mass-produced electronic-oven magnetrons whose material and assembly labor content is similar to the proposed generator. The cost of the Schottky-barrier diodes in the rectenna was projected on the basis of the basic material content and the use of experience curves typical of the semiconductor device industry.[28]

The estimate of transportation costs is based upon a completely reusable space shuttle to transport material from the ground to near-earth orbit and the use of space tugs equipped with high-specific-impulse electric propulsion to transport material from near-earth to synchronous orbit. The estimate given in the "low" column of the table is associated with a second-generation earth-to-near-earth-orbit system.

All component and system costs are assumed to be an average cost associated with the tooling for and the manufacture of 20 or more nearly identical systems. The development costs of the first prototype cannot now be estimated accurately but it is assumed that this cost spread over a production of 20 or more systems represents only a small fraction of the costs listed in Table II.

Number of SSPS systems and land use

The number of SSPS systems that might be deployed is dependent upon their economic viability. Any discussion of the number deployed and land use must be placed in the context of the year 2000 or thereabouts. At that time, the projected requirement is for two million megawatts of electric power generation.[1] This requirement is staggering but it still does not take into account such distinct possibilities in that time period as electric propulsion of automobiles or forced abandonment of fossil fuels for heating purposes. If the requirement were to be met by conventional generating stations rated at 1000 MW each, a quantity of 1600 such plants would be required. If these were all located offshore so as to minimize impact upon the land environment, there would be an average of one generating station approximately every 5 km along the entire U.S. coastline, exclusive of Alaska and Hawaii. This absurd example illustrates not only the magnitude of the requirement but the necessity of a variety of approaches to the energy problem.

I. Microwave power transmission efficiencies

	Efficiency Presently Demonstrated*	Efficiency Expected with Present Technology*	Efficiency Expected with Additional Development*
Microwave power generation efficiency (η_g)	76.7†	85.0	90.0
Transmission efficiency from output of generator to collector aperture (η_t)	94.0	94.0	95.0
Collection and rectification efficiency (rectenna) (η_r)	64.0	75.0	90.0
Transmission, collection, and rectification efficiency ($\eta_t\eta_r$)	60.2	70.5	85.0
Overall efficiency ($\eta_g\eta_t\eta_r$)	26.5‡	60.0	77.0

* Frequency of 2450 MHz (12.2-cm wavelength)

† This efficiency was demonstrated at 3000 MHz and a power level of 300 kW CW.

‡ This value could be immediately increased to 45 percent if an efficient generator were available at the same power level at which the $\eta_t\eta_r$ efficiency of 60.2 percent was obtained.

II. Estimated capital costs of SSPS power generation ($/kW)

	Confidence Factor		
Cost Element	Low p = 0.25	Medium p = 0.50	High p = 0.75
Solar array	610	1100	1870
Microwave	60	120	190
Rectenna	30	50	70
Transportation	190	450	810
Land	*	*	*
Total	890	1720	2940
Probability estimate	1400	2100	2600

*Negligible

The terrestrially based portion of the SSPS system, by virtue of its low pollution and no need for a coolant, is well suited to the inland areas of a country. There is, then, a desire to find land areas that are either wasteland, or at least marginal from an economic use point of view. To such land areas may be added low-cost land that may be located within a reasonable distance of even our most populous areas. Without some drastic reversal of the present declining birth rate and the present flow of the population from rural regions to urban centers, many sparsely populated land regions will remain available as sites for rectennas in the year 2000. This is particularly true of the arid regions of the Southwest and the Great Plains.

To be an important factor in supplying the base-load requirements in the year 2000, the SSPS system would have to supply about 500 000 MW. This figure corresponds to a quantity of fifty 10 000-MW systems, each requiring about 40 km² for the rectenna and a protective guard ring. The total land requirement would be 2000 km². This is an insignificant portion of the marginally useful land that is still expected to be available in the year 2000.

Side effects of the SSPS system

The freedom of the SSPS from any pollution in the form of chemical, particulate, or nuclear wastes has been mentioned. It also has a very low thermal pollution as the result of the very high efficiency of the rectenna, the only terrestrially based part of the system. Three possible side effects whose seriousness should be evaluated, however, are biological effects, RFI, and weather modification.

From the viewpoint of general biological effects[29,30] of microwave energy upon man and other forms of life, the only effect that has been established after many years of investigation and observation is the heating effect, now used beneficially in the home electronic oven and in industrial processing. The heating effect is relatively benign biologically and man has the relatively high continuous-exposure tolerance of 10 mW/cm². The continuous exposure standard in the U.S. is set at that level.

The maximum power density of microwave radiation in the base-line SSPS system is at the center of the rectenna and its value is a little less than 100 mW/cm² less than that of solar radiation but ten times the density of the U.S. continuous exposure standard. The intensity level falls rapidly near the skirts of the microwave beam and reaches levels of a few μW/cm² within a few kilometers of the outer edge of the rectenna. A reasonable guard ring and fence around the rectenna should prevent any damage to humans or wild life in the general area. Within the confines of the rectenna area, wild life would probably be excluded and maintenance personnel would take suitable precautions.

The impact of the beam upon metal-skinned aircraft that fly through it should be minimal because almost all of the energy impinging upon the aircraft would be reflected. For fabric-covered planes and plastic-cockpit helicopters or airplanes, the occupants would be exposed to the beam for the period of time required to fly through it. The impact upon birds is a special problem that needs to be studied. Location of the rectenna in comparatively desolate areas and away from the migration lanes of birds should minimize this aspect.

In concluding this brief discussion of biological effects of the SSPS, it should be noted that despite the lack of identification of any effects of microwave radiation other than thermal, there is agreement that the study of biological effects of microwaves should be continued, particularly with respect to any long-range or delayed effects. This concern has been recognized by the U.S. Government and is identified with a proposed Government-supported comprehensive study of the nonionization aspects of microwave radiation. The results of this and other studies that may be made would determine the extent of the guard ring around the rectenna and the range of choice of geographical area for rectenna installation.

The side effects associated with RFI are expected to be more important than the biological effects. Since the microwave beam portion of the SSPS system is not intended to handle information, no bandwidth is required for that purpose. However, a transmitter of this power level will inherently generate a large amount of noise, which would be scattered physically outside of the microwave beam. The intensity of this noise would be greatest near the frequency assigned to the SSPS system, just where the use of filters is the least effective. It would be desirable, therefore, to assign a frequency band perhaps 100 MHz wide to the system. Initial calculations based upon the measured noise properties of the type of microwave generator proposed for the system and the use of a moderate amount of additional filtering indicate that the CCIR flux density limitation requirement that protects earth-based microwave receivers can be met if a band of 100 MHz is assigned. However, this aspect of the SSPS operation needs a great deal more study.

In the minds of many, it may seem that the proposed use of space for the transmission of power represents a potential intrusion into an area long reserved for the transmission of information and should be permitted only if our future energy problem becomes so great that power transmission through space is an overriding consideration in our system of priorities. But the coexistence of power and information transfer in space should be examined in terms of what communication practices will be in 1990 and 2000—reasonable dates for the first operational SSPS system and for full-scale deployment. The low-frequency end of the microwave spectrum, in which the SSPS would probably be located, is already becoming too restrictive for the large mass of information to be conveyed and, by 1990, almost all land-based communication may be handled in ducted systems using millimeter waves or light waves and spaced-based systems may be using millimeter waves.

It is also observed that, in the past, power and communication have been able to take advantage of a common transmission medium, notably wire transmission, and to resolve the mutual interference problems that have arisen. There may also be a clue to a solution in case interference problems do arise by observing the palliative action that has been taken to override man-made interference in the AM broadcast band by increasing the power level of the transmitter. It is even possible that the synchronous SSPS satellite may become attractive as the physical location for the transmitters of advanced communication systems because of the easy availability of power.

The issue of the microwave beam's impact upon atmospheric disturbances and weather has also been raised. Upon examination, however, it is found that the density of power input to the atmosphere resulting from absorption of microwave energy is typically 20 watts/m². This level is small compared with the density of power absorbed from solar radiation and reradiative processes from the earth. It is doubtful if the beam could produce a significant local disturbance. On a global scale the total energy input to the atmosphere from 100 SSPS systems would be miniscule compared with natural processes.

Time scale for the SSPS

Any proposed time scale for the SSPS development must be made in the context of the possible need for the system, when it may be needed, and the difficulty of the development and deployment. From a strictly technological point of view, the development of the SSPS system may well be less of an undertaking than was the Apollo project when it was first initiated in 1961. Most, but certainly not all, of the basic technology and know-how involved are at hand, either from the Apollo project or from other sources.

Will there be a need for the system? This depends upon whether the approach can be made more cost competitive and upon the experience with other approaches to satisfying our future electric power needs. And here the picture is very clouded. Even nuclear fission has a relatively near-term fuel problem whose solution is dependent upon the successful development of the breeder reactor. In the long term, the bulk of all our energy—including electric energy—must come either from a concentration of the sun's diffuse energy or from nuclear fusion.

If needed, when will it be needed? It is clear that the approaches to achieve our electric power needs for the next two decades have already been set in motion. It should become much clearer in the 1980 time frame whether these approaches will also meet our needs in the 1990 to 2010 time frame and whether nuclear fusion will have progressed to the point where we will have confidence in its capability to help supply our energy needs into the future. It appears that it will be the 1980s, when the SSPS option will be picked up, if there is a need for it.

With this discussion as a background, the appropriate near-term action is clear. A thorough systems study of the SSPS should be made to determine the critical and weak points in the system and to assess if they can be dealt with successfully. If the study continues to indicate a viable system, some development effort on a few long-lead-time items should be initiated. Concurrently with the systems study, development effort should go forward in some of the already established critical areas that have a broader range of application than just the SSPS. Two specific technological areas are solar photovoltaic cells and microwave power transmission. With such a near-term program as a background, the 1980 time frame should be arrived at with a well-organized, well-thought-out program to mobilize our resources efficiently and to build and deploy the complete SSPS system if it should be desirable to do so.

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William C. Brown (F) has been with the Raytheon Company since 1940 where he has contributed many innovations to microwave tube technology. He was educated at Iowa State University (B.S. degree in electrical engineering) and Massachusetts Institute of Technology (M.S. degree). For a period of two years prior to joining Raytheon, he was with the Radio Corporation of America. Mr. Brown is a recognized authority on magnetrons and, in 1953, he applied the crossed-field energy-conversion principle to an efficient broadband amplifier device known as the Amplitron, or the reentrant-beam, crossed-field amplifier. In the recent time period, he has devoted his attention to the improvement of the overall efficiency of microwave power transmission and to the establishment of its credibility within the scientific and engineering community. He has also been involved in developing the details of a microwave power transmission system suitable for use in the Satellite Solar Power Station concept. Mr. Brown has had 43 U.S. patents issued to him and is the author of more than 25 technical articles.

Special report

Energy: Crisis and challenge

After a century of feasting, the U.S. now finds itself facing a fuel famine, with no immediate end in sight

Gordon D. Friedlander Senior Staff Writer

In Chicago, this past winter, Commonwealth Edison was forced to shut down gas fired boilers that delivered steam to a 96-MW turbogenerator. In Iowa, a natural gas scarcity forced farmers to dump their wet corn harvest because their crop dryers could not be operated. In Denver, the city school system was shut down for lack of fuel oil. These are not isolated occurrences: most industries in the western states including electric utility generating plants have been served for *many* years under an "industrial interruptible" gas schedule, shifting to fuel oil during severe cold spells or shutting down. Along the eastern seaboard and throughout the central states, the fossil fuels, oil and gas, have reached dangerously short supply, barely enough to meet domestic and commercial requirements. Both the states affected and the fuel suppliers were forced to ration reserves.

And throughout this crisis, ironically, the most polluting of fossil fuels, coal, continued in abundant supply. The seemingly inevitable consequence of this abundance: the United States, the world's wealthiest and most pollution-conscious nation, will undoubtedly be forced to increase greatly the production and use of coal, a fuel which not only is responsible for the pollution of the atmosphere in vast areas of the country, but is obtained primarily through strip-mining, a process not noted for its kindness to the landscape in the 38 states in which the fuel is readily available by this method.

Background to the dilemma

As the world's wealthiest nation, with the highest standard of living, the demand for labor-saving devices, creature comforts, and luxuries in the United States is without parallel. And the kilowatt-hour has been the servant that has abetted this demand. The U.S., like most other technologically advanced nations, has behaved for decades (despite certain recog-

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We have sufficient uranium ores for nuclear fission, but . . .

There is a great deal of interest in the potential of geothermal power, but the technological problems are still vast, and harnessing this natural power will be costly, but . . .

Coal is plentiful—if extensive strip mining is permitted there should be more than ample for . . .

by 1985, more than 50 percent of our petroleum will have to be obtained from overseas sources.

1985, or earlier, may see a number of geothermal power plants on the line, capable of generation in the megawatt range (in addition to three plants presently in operation).

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nized good intentions) as if there would be no tomorrow and its fuel and energy sources were inexhaustible. It has squandered its resources with the gay abandon of the legendary playboy who uses ten-dollar notes to light his cigarettes. If you doubt this contention, drive into any major U.S. city at night and observe the myriad of high-rise office buildings illuminated from top to bottom while cleaning crews do their chores. Similar, if not always as blatant, examples of waste are seen throughout the world.

J. W. Simpson, president of the Power Systems organization of the Westinghouse Electric Corp., believes that the United States is fast becoming a "have not" nation because of its enormous consumption of cheap energy resources. And although experts on the subject are making widely divergent estimates of the country's fossil-fuel reserves, demand is presently outpacing the production of these fuels; thus, fuel costs are rising and will continue to do so. An unfortunate factor in the total picture is that natural gas, the fuel with the least adverse environmental effects associated with its combustion, has become the scarcest.

The blame for the fuel shortages and their certain, adverse impact on the economy can be placed at several doors: Government, regulatory agencies, suppliers, and the general public—for reasons that will be developed in the context of this article.

Energy: feast to famine in 1.2 centuries. For the 120 years following the dawn of the Industrial Revolution, the United States enjoyed what promised to be a virtually limitless supply of fossil fuels for conversion into thermal, mechanical, and electric energy. Since the turn of the century, cheap and inexhaustible electric power for industry and the public seemed an attainable goal.

But then, in the 1940's, it was announced that "the demand for electric energy in the U.S. is doubling every decade." This "exponential growth cliché" has been repeated *ad infinitum* since that date. Now the implications of this geometric progression become somewhat ludicrous when one considers that—theoretically, at least—at some not-too-distant future date, every available land site in the country could be occupied by a generating station! In practical terms, however, the saturation point must come (for environmental and fuel reasons) by the year 2000.

The complexities of synthetic shortages. As indicated at the outset, the fuel-famine phenomenon is extremely complex in its ramifications and is interlocked—almost in the manner of an ecological chain—by many factors, some of which are aggravating the situation by approaching it at cross purposes. The contrived aspect of the fuel-shortage problem, in itself, is multifaceted and includes

- The serving of special interests.
- Real (and/or imaginary) fears of environmentalists, ecologists, and conservationists.
- Advertising (now largely discontinued) to urge the use of more electric and gas appliances and/or heavy equipment.
- Myopic planning for the future, with few or no firm energy-control policies or guidelines at the state and Federal levels.
- International political and balance-of-trade considerations.
- The enormous fuel demands of the military during the war in Vietnam.

In descending order of priority, fuels whose availability relates to the overall famine are: natural gas, oil and coal.

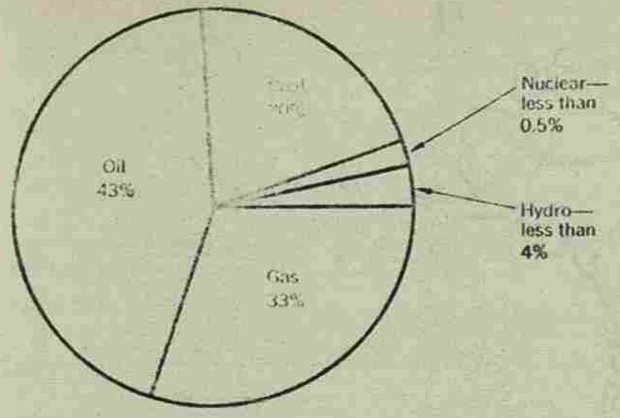
Natural gas: one third of the energy pie

Natural gas, as indicated in a recent background report prepared by the American Gas Association, provides 33 percent of the total energy requirements of the U.S. (Fig. 1). There is a critical need for new domestic supplies to meet unprecedented demands by industrial, commercial, and residential consumers. This need is recognized by all segments of the gas industry—producers, pipeline owners, and distributors—as well as spokesmen for the U.S. Department of

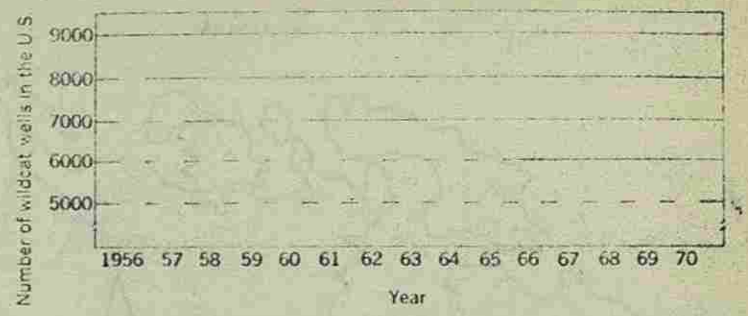
we could be in trouble by this target year unless an operational fast-breeder reactor (FBR) is developed, or a nuclear fusion breakthrough occurs.

its increasing use, especially in power, over the next 25 to 30 years . . . up to and beyond the year 2000.

By the year 2000, solar energy which presently suffers from a lack of funding—and general interest—will be of major importance in meeting the world's energy and electric generation needs. . . .

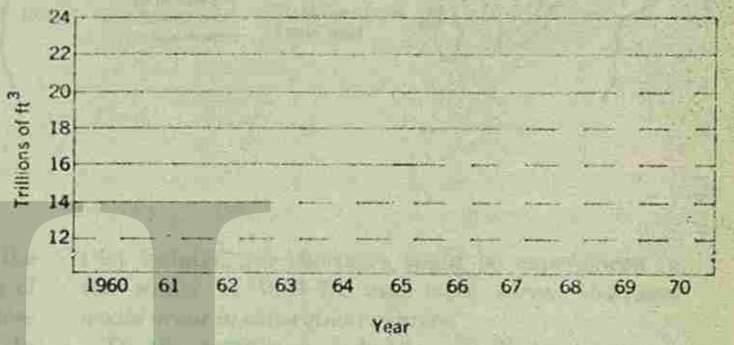


[1] "Pie" chart showing sources of energy in the United States at the present time.



[2] Bar graph indicating the decline in the number of wildcat drilling operations in the petroleum industry over a 14-year period. Natural gas is generally found in conjunction with oil deposits.

[3] Production of natural gas between 1960 and 1970 reflects a 6 to 8 percent increase annually in the demand for this fuel.



the Interior and the FPC. (The situation was also recognized by President Nixon in his special message to the U.S. Congress in June 1971.)

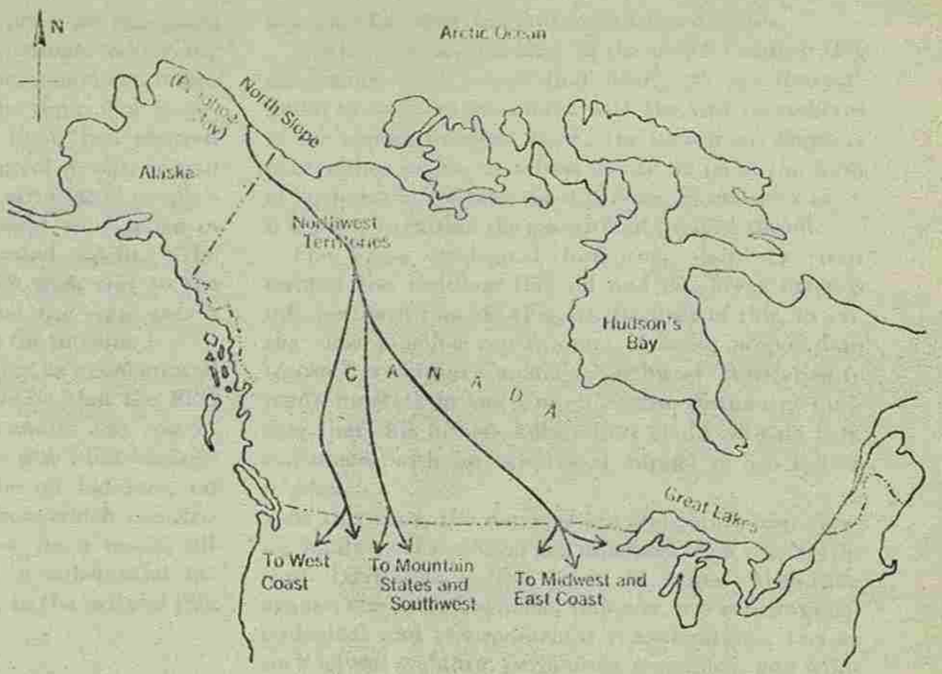
In fact, an FPC staff briefing, published April 15, 1971, states flatly that evidence submitted to the commission "confirms beyond any doubt, if indeed there is any remaining doubt, that a serious gas-supply shortage does in fact exist throughout the nation's gas-supply areas."

It is ironic that there is an actual shortage of natural gas amidst a domestic potential of plenty. Let's review, in retrospect, some of the reasons that have led up to this paradox.

The present shortage did not happen overnight; rather, it is the result of trends over the past two decades that have burgeoned into today's crisis. From the late 1950s, and through the '60s, the possibility of a future gas-supply problem was vigorously debated. But within this time frame, the exploration and drilling activities of the petroleum industry declined markedly (natural gas, of course, is usually discovered in conjunction with oil deposits). Wildcat drilling, a sensitive gage of these efforts, decreased by 40 percent between 1956 and 1970. And, since 1962, more than 200 drilling rigs were removed from the U.S. and transported to more attractive—and profitable—business opportunities in other areas of the world. Figure 2 reflects the steady decrease in wildcat wells from 1956 through 1970.

The demand for natural gas during the decade of the 1960s increased sharply—running from 6 to 8 percent annually from 1965 to 1970 (Fig. 3), and from 8

The early part of the 21st century will probably witness operational MHD generation in the megawatt range, and thermionic conversion—by means of which nuclear energy will be converted directly into electric energy, thereby eliminating the conventional steps of generating steam to drive turbogenerators. This era will most likely see the widespread harnessing of energy developed by the earth's rotation (wind and tidal power). Laser transmission of power over great distances may also be a revolutionary development . . . and who knows what undreamed of possibilities may take place 30 to 50 years from now?



[4] Routes of potential natural gas pipelines from Alaska's North Slope and Canada's Northwest Territories to various consumer regions in the "lower 48" states.

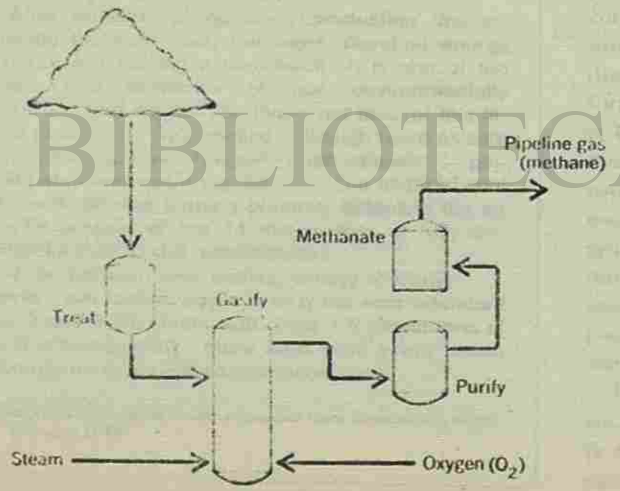
to 10 percent a year up to the present time. Thus, the reserves-to-production ratio, a much debated index of gas supply and demand, has decreased from more than 21 years' supply in 1956 to less than 14 years, in 1970.

Demand for economic incentives. As far back as December 16, 1968, the president of the American Gas Association, in a letter to the FPC, warned that distributors were having difficulties in contracting for increases in long-term gas supplies. The communication urgently recommended that the FPC act to provide additional "economic incentives" for exploration and development.* And, in June 1969, ten distributor executives, representing about 40 percent of the gas industry's customers, met with the FPC to reaffirm that isolated gas shortages could be experienced in the winter of 1969–70, and *more severe shortages would occur in subsequent winters.*

To the petroleum industry, the Federal government, through the FPC, is the villain responsible for the scarcity of natural gas through price regulation. The industry spokesmen note that the major oil producers supply 75 percent of the natural gas in the U.S. Since gas is the only fossil fuel that is still price controlled, the producers feel that the economic incentive is insufficient to make the exploration and development of additional gas sources profitable—or feasible.

Bubble, bubble, flares, and trouble. Because the oil industry believes the price of natural gas to the consumer to be too low to warrant the construction of costly pipelines from offshore platforms—and even from land-based refineries—it is not uncommon to see gas being flared or bubbling up through the waters of the Gulf of Mexico. Thus we have the spectacle of precious gas reserves being flagrantly wasted becaused of economic policy disagreements. Although the oil companies readily justify this procedure (and freely admit that there are vast untapped gas fields underwater), there is a feeling among some critics that the public is being subjected to economic pressure by the producers. Thus the nub of the matter may be whether the producers will supply the consumers' gas demand requirements at a fair and reasonable profit or whether they are intending to "sit on" the undeveloped gas supplies until an economic windfall is assured. In short, why accept a wellhead price of 25 cents/1000 ft^3 if the FPC will relent under

[5] Simplified process-flow diagram indicating the various steps required in coal gasification.



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* In the view of the Ford Foundation (see "Ford, Fuels, and Your Future," *IEEE Spectrum*, pp. 59-60, Oct. 1972), present Federal government policies are contradictory and outmoded. For example, Government tax policy encourages exploration for natural gas—and the FPC's price controls discourage it!

pressure and permit twice that price as the going rate" (It is not our intention to comment editorially on the subject of excess profits, but merely to recognize that controversy surrounds the topic. For example, Alaska's Governor William Egan has charged that the oil industry has amassed great wealth around the world because of "a license to steal other people's resources," promising that this would not happen in Alaska with regard to the anticipated pipeline. The Governor's concern is not so much with cost to the ultimate consumer, but rather that the state gets a substantial share of the profits from the pipeline.)

But the joker in the deck, insofar as economics is concerned, is the industry's contention that the FPC either does not know or underestimates the cost of providing natural gas. This may be true – but because all such figures emanate from the oil industry, no outsider, even Government, has facts which can dispute the industry-provided figures. As a result, all present indications point toward a substantial increase, sanctioned by Government, in the price of this vital fuel.

Relief from Alaska?

Gas under the roof of the world. A recent Government report, "Potential Supplies of Natural Gas in the United States," estimated that there is about 325 trillion cubic feet of natural gas deposits in Alaska (as compared with an estimated 850 trillion ft³ in the entire contiguous 48 states).

Currently, there are three principal study groups – including major U.S. and Canadian gas companies – conducting comprehensive analyses of feasible overland pipeline routes (Fig. 4) from Prudhoe Bay (North Slope) to various regions of the "lower 48." Each group tends to feel that the economics of such a complex gas pipeline project for transmitting the Alaskan fuel can compete favorably with other forms of energy found in the contiguous United States.

Further, the leaseholders of the major Prudhoe Bay discoveries have stated that nearly all gas deposits found to date are associated with the vast oil reserves of the region. In other words, the known gas deposits exist either as gas dissolved in the oil or in the form of "cap gas" overlying the oil. Thus, in neither case is it feasible to extract the gas without tapping the oil.

The same geological formation, however, that created the Prudhoe Bay oil and gas areas extends into northern Canada (Fig. 4). Because of this, extensive new pipeline construction is being proposed to transmit gas from Canada's Northwest Territories to ready markets in the United States. Estimates indicate that this billion-dollar effort could provide U.S. consumers with an additional supply of 1.5 billion ft³/day.

At this time, the major study groups are also making analyses of overland gas pipelines from the Northwest Territories to the lower 48 states. Militating against the overall scheme, however, are controversial ecological and environmental considerations; factors such as soil stability, permafrost regression, and wildlife habitats in Alaska must be seriously contemplated.

Liquid natural gas. Liquefied natural gas (LNG) in small, but ever-increasing percentages, is being supplied by importation to the U.S. in special cryogenic tanker ships from Libya, Algeria, Venezuela, and other overseas gas-producing regions. The gas is liquefied by cooling it to 147°K. In its liquid state, the gas occupies less than 0.2 percent of its gaseous volume. Very large investments are presently being made in the construction of storage facilities to make LNG available at least in coastal cities of the U.S. (However, the LNG land-based storage facility program, especially in densely populated areas, suffered a severe setback last February when 40 workmen, who were cleaning an empty tank, were killed in an explosion and subsequent fire of undetermined origin.) Several of the unique tanker ships are now in service and more are under construction for service by 1975. And, in 1985, a fleet of 80 such vessels should be available for LNG transport. In all probability, however, LNG will continue to be used for power peaking only.

Coal gasification. Figure 5 is a simple flow diagram of the basic coal-gasification process. Although the illustration is straightforward, the technique encompasses a complex chemical transition of solid coal into a form of natural gas. Essentially, boiler-produced steam is reacted with the carbon in coal to form a hydrogen-enriched gas similar to methane (CH_4). But in the reaction, ammonia (NH_3), carbon dioxide (CO_2), and hydrogen sulfide (H_2S) are also produced. In the following sequential steps, the gaseous products are treated, cleansed, and purified to remove the NH_3, CO_2, and NH_3, and leave a "methanate" consisting of CH_4, hydrogen (H_2), and carbon monoxide (CO). The methanate, however – although combustible – is low in calorific content by comparison with "natural" natural gas.

The ultimate, and most difficult, phase of the process is to increase the calorific content of the basically CO gas by further chemical reactions with H_2 to raise the methane content. This is accomplished at

The King is dead . . .

Old King Coal has a dirty old soul . . .
In a hole in the ground lives he
He smells from his smoke,
And he coughs from his coke,
And he pulls for his polluters three
(particulates, fly ash, and SO_2).

Jane Stein,* writing in the February 1973 issue of the *Smithsonian*, puts it this way:

"After decades of declining production and increasing disfavor, coal, our most abundant energy resource [is] staging a comeback. It is one of the ironies – and dilemmas – of our environmentally aware age that we will use more, not less, of this filthiest of fuels. . . . Strip mining, although twice as safe as [pit] mining, has left lunarlike landscapes . . . polluted rivers and water supplies . . . . The blight of coal continues into the burning process, befouling the air with 60 percent of the 14 million tons of SO_2 discharged a year by U.S. smokestacks . . .

"In desperation over coming energy shortages . . . planners are turning again to dirty but ever-abundant coal, found in 38 states with some 1.5 trillion tons of it still [underground] – more than 1000 years' worth at today's recovery and consumption levels . . . ."

*Copyright 1973 Smithsonian Institution from Smithsonian Magazine, February 1973.

temperatures of about 1100°K, and very high pressure (more than 65 atmospheres).

The first pilot plant in the U.S., designed to convert coal directly into pipeline-quality "natural" gas, is presently in operation in Chicago. This plant will determine the feasibility of coal gasification over the next several years.

Development of a viable coal-gasification process will release a major new source of gas supply. It is estimated that, by means of economic conversion, about 11 000 trillion ft³ of such gas could become available—enough to supply the gas-energy needs of the U.S., at present consumption rates, for 500 years!

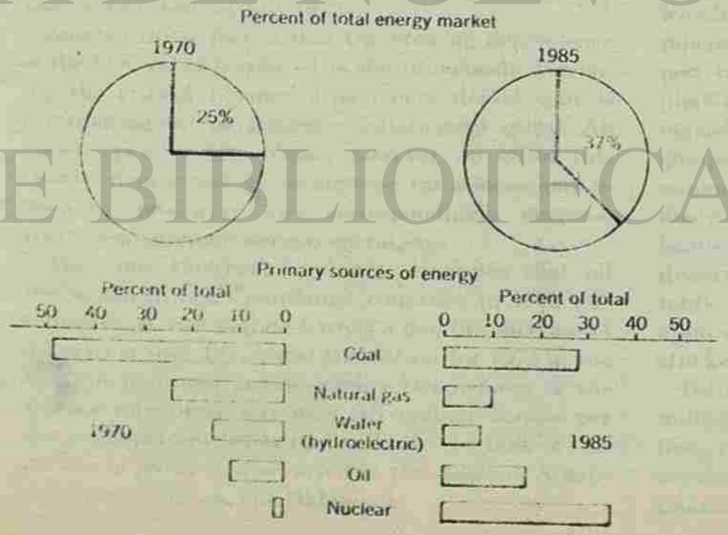
Oil: 43 percent of the pie

As we have noted, the supplies of oil and natural gas are closely interrelated since gas is generally found in connection with petroleum deposits. By referring again to Fig. 1, we see that oil commands the largest slice (43 percent) of the total energy pie. But this past winter also witnessed a dearth of light fuel distillate—which includes oil for domestic heating—and a similar shortage occurred in supplies of jet aircraft (kerosene base) and diesel-engine fuels.

Fortunately, for the areas in which acute shortages were felt, state agencies promptly jumped into the breach to form emergency fuel-distribution pools. Further, a generally milder-than-expected winter in the affected regions helped to mitigate the crisis.

. . . But plenty of gasoline. However, if there was a scarce supply of these products of fractional petroleum distillation, it was certainly not noticeable in the abundance of gasoline available for motor vehicles. The reason for famine pockets in the overall fuel feast is that petroleum refiners are reaping much higher profits from the production of gasoline than they are from fuel oil (which had been subject to Phase 2 price controls).

[6] Energy usage by electric utilities in the U.S. Left-hand portion of graph shows the percentages of various energy sources as of 1970; right-hand graph indicates the projected percentages of these same sources in 1985.



For example, during the first week of January 1973, U.S. refineries produced 45 million barrels of gasoline versus 21 million barrels of oil for domestic heating—a ratio of more than 2 to 1. Thus it does not require a quantum jump in the power of prediction to conclude that, under Phase 3's loosening of the price-control reins, more fuel oil will be available—at a higher cost. Nevertheless, industry, the utility companies, and commercial enterprises fear the continuation of an uncertain fuel-supply situation in which sporadic short-term shutdowns may be inevitable this year.

The import quotas. One of the primary elements underlying the fuel oil quandary is the fact that the U.S. Government controls the domestic oil supply by restricting the amount of petroleum U.S. companies can import from overseas. These import quotas were introduced back in 1959 for the dual purpose of

- Serving as a national defense measure to ensure an adequate domestic supply and reserve.
- Providing a protective barrier to keep out the cheaper oil from the Mideast and South America.

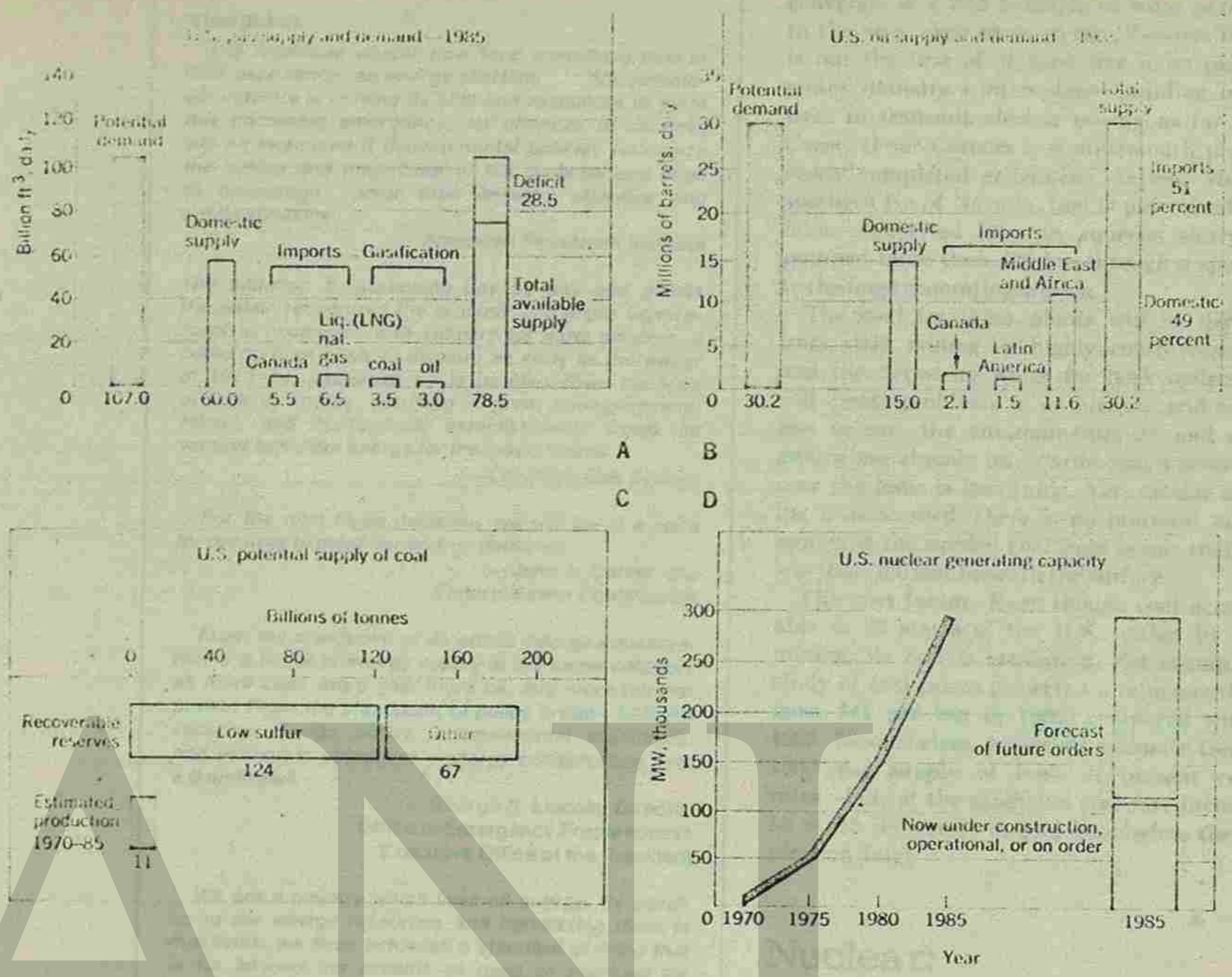
Ironically, the impact of the quota has been to keep domestic oil prices high and supplies low. In this way, the protectionist safeguard—as well as the national defense consideration—has backfired. Actually, overseas oil is so plentiful and inexpensive that much more of it would be imported, except for our complicated quota restrictions. (In sections of the Mideast, oil is extracted at a cost of 20¢ a barrel—contrasted with $2.00 per barrel in the U.S.)

But, in a reversal of a 13-year policy, the U.S. Government—because of the fuel oil crisis—was forced to relax the quotas over a four-month period last winter and increase the overseas importation of home-heating oil by one million barrels a day. One of the paradoxes of the Government's theory that more investment should be applied to the domestic exploration and production of petroleum is that many major U.S. companies have gone overseas to build their refineries—notably in the Caribbean, Venezuela, and the Middle East—for two salient reasons:

1. There is a larger supply of crude oil *outside* of the U.S.
2. Taxes on a U.S. oil company's overseas profits are *lower* than taxes on its domestic enterprises.

Too little too late? In 1970, a Nixon-appointed task force estimated that import quotas forced the price of domestic oil up by $5 billion a year (representing an extra fuel bill of $24 annually for every U.S. citizen).

Unfortunately, under rapidly changing economic conditions—notably the devaluation of the dollar, sharply increased royalty payments demanded by overseas sources, and much higher transportation costs—imported oil is hardly the bargain it used to be. In fact, an article in *The New York Times* of March 5, 1973, alleged that an unpublished U.S. Government study indicates that U.S. refineries now pay more for some overseas crude than for domestically produced oil. This information has apparently been confirmed by oil industry sources. The primary reason for this surprising cost reversal is that demand (on a worldwide basis) was more than supply in 1972. As a



[7] A—Projected natural gas supply and demand (in terms of billions of cubic feet daily) from all sources—and artificial processes—by 1985. B—A similar projection with respect to the oil situation 12 years hence. C—Horizontal bar chart of estimated coal reserves. D—Projection of nuclear generating capacity between 1970 and 1985.

present cost example, Libyan crude oil transported to the port of Baton Rouge, La., commanded a price of $4.56 per barrel as of March 1, compared with a top price of $4.07 a barrel for domestic offshore oil. Further, the Libyan price represented a 90¢ per barrel hike over the level of July 1972.

Another ironic fact is that the growing dependence of the U.S. on imported oil is simultaneously worsening the critical balance-of-payments deficit and is contributing to the domestic inflationary spiral. An option open to Mr. Nixon, however, to offset this countertrend would be to increase tax concessions to domestic producers and correspondingly decrease concessions granted overseas operations.

The same Government report stipulates that oil production in non-Communist countries in 1972 was estimated at 41.8 million barrels a day (an increase of 8.2 percent over 1971). But the output for 1972 in the U.S. (as indicated in preliminary Department of the Interior estimates) was only 9.5 million barrels per day—0.75 percent below that of 1971. The bulk of this decline in production occurred in the states of Arkansas, Illinois, Kansas, and Oklahoma.

The U. S. already imports more than 25 percent of its oil and, according to virtually every survey, future energy requirements will, by 1985, double that percentage (Fig 6). Clearly some sort of Federal action must be taken. [*Editor's note:* At press time, President Nixon had announced that he had acted to terminate the oil import quotas.]

The trans-Alaskan pipeline. Since the discovery of large oil deposits in the Prudhoe Bay region of Alaska's North Slope several years ago, the major oil leaseholders have been trying to build a 1300-km-long pipeline to transport the crude from its source to the port of Valdez on the Gulf of Alaska. The proposed pipeline, however, triggered a widespread storm of opposition from conservationists and environmental groups, and the seafood interests at Valdez—a major seaport for the Alaskan fishing fleet and canning industry—who fear that oil spills from supertankers loading at the terminal end of the pipeline would be disastrous to the existence of the town and its inhabitants. Thus, although the pipeline scheme has been approved by the Interior Department, litigation is still keeping the construction project in limbo.

Oil company experts estimate that a peak of 2 to 3 million barrels per day could flow through the pipeline, thereby easing the petroleum situation in the contiguous 48 states. But some authorities on fuel problems question, aside from environmental consid-

Viewpoints

The American people now face something new in their experience: an energy shortage . . . The petroleum industry is rallying its skill and resources to meet this oncoming emergency. Its chances of success will be increased if Governmental policies recognize the nature and magnitude of the problem and seek to encourage, rather than impede, effective and timely solutions

—American Petroleum Institute

The situation is worsening day by day and unless the public recognizes the problem and urges Government to cooperate with industry for early solution, it could go from crisis to disaster as early as the winter of 1973-74. Industries could be shut down because of lack of energy, resulting in great unemployment; homes and commercial establishments could be without sufficient energy for their daily needs.

—Columbia Gas System

For the next three decades, we will be in a race for our lives to meet our energy demands.

—John A. Carver, Jr.,
Federal Power Commission

From the standpoint of its effect, energy conservation is a factor in energy supply in the same category as more coal, more gas, more oil, and more nuclear power. From the standpoint of policy areas—national security, foreign policy, environmental objectives, and economic objectives—energy conservation gets a double plus.

—George A. Lincoln, Director
Office of Emergency Preparedness
Executive Office of the President

We are a country which lives on energy. By developing our energy resources and harnessing them in machines, we have achieved a standard of living that is far beyond the dreams of most of mankind for most of history. Overwhelming evidence points to the fact that a close correlation exists between living standards and energy use. Not surprisingly, nations with the highest living standards also rank at the top in per capita energy use.

—Edison Electric Institute

Crude oil reserves in the lower 48 states are now at the lowest point in 20 years, while natural gas reserves are at the lowest since 1957.

—Mobil Oil Company

erations, whether the trade-off of the large investment in building the pipeline versus the limited number of years of peak production is worthwhile.

Coal: up from the ashes

Paradoxically, coal, the most polluting of the fossil fuels, is also the most plentiful source of energy and it presents the U.S. with its major hope of meeting the fuel/energy crisis. It is still used to fire boilers for the generation of 55 percent of all steam-electric power in the country—although it accounts for only 20 percent of the total energy pie in Fig. 1. The controversial "Four Corners" plant (see p. 20), situated where the states of Utah, Colorado, Arizona, and New Mexico converge, is a bad example of what pollution can do to the once clear skies of the "Golden West." And it is but the first of at least five more plants that the power industry contemplates building in the Southwest to transmit electric energy as far as the West Coast. (Four Corners is a minemouth plant, but at a newly completed generating station, Mojave, at the southern tip of Nevada, fuel is pulverized at a distant mine, converted into an aqueous slurry, and then pumped more than 430 km through a special pipeline to the huge generating station.)

The coal for these plants will be derived mainly from strip mining—a highly controversial method—and the necessary water for both boilers and slurry will create problems in an already arid region. Needless to say, the environmentalists and conservation groups are already up in arms and a protracted battle over the issue is inevitable. Yet, insofar as strip mining is concerned, there is no practical alternative to removing the needed coal from seams that are usually less than 200 feet beneath the surface.

The cost factor. Even though coal is readily available in 38 states of the U.S., either by pit or strip mining, its cost is escalating. For example, a recent study of coal prices projected a minemouth cost of almost $11 per ton in 1985, compared with $3.92 in 1968. Nevertheless, geologists estimate that there is a 1000-year supply of coal—at present consumption rates—but, at the predicted cost-rate increase, it may be worth its weight in gold long before the supply expiration date!

Nuclear: increasing—but too slowly

The energy crisis in the U.S. is getting more acute because we are not able to maintain our nuclear generating plant construction program according to plan. For example, at the beginning of 1972, nuclear generation was behind schedule by 15 000 MW; by January 1, 1973, the deficiency had doubled to about 30 000 MW. Present indications are that the deficit will become increasingly severe with the passage of years. Thus our already strained fossil-fuel reserves are dealt another setback, because each 10 000-MW annual deficiency in nuclear generation requires that 100 million more barrels of oil must be consumed as a substitute. At present, the annual shortage in the U.S. is some 300 million barrels—or about 820 000 barrels per day.

But, over the long haul, we may be in even more serious nuclear trouble because present state-of-the-art generation by nuclear fission is only a temporary answer. Although the U.S. *now* has a surplus of uranium ores, there may be a shortage by 1990—unless a major push is made in developing an operational fast-breeder reactor (FBR), or there is a dramatic breakthrough in power generation by nuclear fusion. Hopefully, both the AEC and the Federal government are now committed to an all-out effort to achieve these objectives.

Figure 7 consists of bar graphs that indicate and project (1) gas supply and demand, (2) oil supply and

Editor's note: This is the introductory article of a series in which qualified authors will present their diverse viewpoints on the fuel and energy crises. This first article presents an overview of the general situation, including some options representing possible solutions to the problems. Subsequent articles will elaborate upon the views of those active in the power industry, fuel production, government, and environmental protection. It seems inevitable that the series will generate controversy, which, hopefully, may encourage dialogue leading to a positive energy policy and program.

demand, (3) potential supply of coal, and (4) nuclear generating capacity in the U.S. between the years 1970 and 1985.

Other sources of energy

Among the short- and long-term practical source development possibilities[1] are solar energy, geothermal energy, chemical batteries (such as lithium-sulfur), and fuel cells. Their merits have been discussed in some detail in previous *IEEE Spectrum* articles by this writer and other authors. Suffice it to say, these R&D programs generally suffer from either a less than all-out commitment or lack of adequate funding from both Government and private sources—or both.

However, according to Charles A. Zraket, of the Mitre Corporation, the two options for the long term (year 2000 and beyond) that should be pursued much more vigorously include solar energy for large-scale power needs, and the possible use of hot, dry rock from geothermal sources well below the surface of the earth (from 3000 to 5000 meters deep) as a regional supplement for energy. He points out that a solar energy system has already been studied that will produce hydrogen fuel, which can then be used in the "hydrogen economy"—notably for fuel cells.

In the nuclear energy area, he contends that, in addition to the liquid-metal fast-breeder reactor (LMFBR), much more emphasis—for both environmental and economic reasons—should be placed on the high-temperature gas-cooled reactor, the heavy-water reactor, and the molten-salt breeder reactor. Also, more R&D should be given towards fusion reactors, especially laser function.

By the turn of the 21st century, Zraket believes that nuclear energy will be used for the base load in the overall energy system—including both electric power needs and as a source for powering electrified vehicles and mass-transit systems. Finally, he feels that the international implications of the nuclear fuel cycle must be addressed with respect to uranium enrichment and the processing and transportation of fuels and waste.

A guessing game in oil and coal

As long as decisions are being made under the improvised energy policies that were devised before the urgent need for a national "master plan" became apparent, the U.S. can neither address nor accurately assess the dimensions of the fuel/energy crisis. Thus there is an uneasy feeling in some quarters that present policies are contradictory, outdated, and outmoded. •

In the realm of "guesstimation," we have seen a plethora of reports (seldom in agreement) from Governmental agencies and private organizations as to whether there is really an energy crisis, a shortage of fuels, and an inevitably upward price surge. (In this context it is interesting to note that last March the Administration reimposed controls on gasoline, restricting this fuel to a 1.5 percent maximum price increase to ensure more production of oil for domestic heating and industrial use.)

Meanwhile, Sen. Henry M. Jackson (D-Wash.), chairman of the Senate Interior Committee, resumed hearings last February 22 on the committee's examination of the present fuel shortages. The hearings were held as part of the U.S. Senate's National Fuels and Energy Policy Study authorized by the 92nd Congress. In Jackson's words: "There has been an apparent breakdown in our national energy system. Serious shortages still persist in many parts of the country. The committee needs to know why it has not been possible to anticipate and meet the demand for various fuels. We are particularly interested in what role Government policies have played in creating the present situation."

On April 10, Sen. Jackson released a staff analysis of Federal energy organization, prepared for the Senate's national fuels and energy policy study. At the time, Sen. Jackson expressed surprise that until very recently almost no formal consideration was given to the manner in which the Federal government is organized to administer energy policy. He alleged that, when the Senate study began, there was not even a good description of the existing Federal energy organization available!

Continuing on this theme, he said, "in the course of its study . . . the staff has identified 64 agencies which administer programs or implement policies that probably were not intended to be energy oriented . . . There is little doubt that this multitude of agencies can be better organized and directed that it has been in the past. It is increasingly clear that, as new, more comprehensive national fuel and energy policies are developed, the implementation of these policies will depend upon a more effective organization . . ."

Based on Sen. Jackson's statements, and other critical analyses, there will inevitably be those who will call for a centralized Federal "Fuel and Energy Agency," perhaps at Cabinet level, and similar in policy-making authority to the EPA. We undoubtedly will hear more of this and other proposals in subsequent articles in this series.

The source of the graphic information shown in Figs. 1 and 3 is the U.S. Department of the Interior, Bureau of Mines; the source of Fig. 2 is the American Association of Petroleum Geologists; and the source of Figs. 6 and 7 is the survey, "Outlook for Energy in the United States to 1085," prepared by the Chase Manhattan Bank.

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Fuel/energy crisis

Toward a national energy policy

Forging a consensus from a multitude of conflicting interests and policies is proving a monumental task

Gordon D. Friedlander Senior Staff Writer

In the face of anxious voices proclaiming the imminence, if not the presence, of a national energy crisis, President Nixon has announced a series of actions and proposals, which, he hopes, will precipitate a concerted national commitment to avert what he believes threatens to be a "genuine energy crisis."

Even before the President's address was delivered on April 18, some high Government officials—especially those in Congress—felt that whatever he proposed in his message would probably be too late, and that to be effective, "it should have been made by President Johnson in 1967." These were not partisan comments, however, seeking to shift the blame from one Administration to another; rather, they were intended to indicate that there are really no short-term solutions to ensure the United States protection from some unpleasant changes in its life style—and even standard of living. (For highlights of the President's message, see the box on pp. 40-41.)

As early as 1952, a Presidential commission realized the need for a Government-inspired and -coordinated energy policy, but today, with our energy demands spiraling, our internal resources seriously depleted, and our economy weakened by an adverse balance-of-trade deficit that precludes indefinitely increasing fuel purchases from abroad, what energy policies exist are promulgated by 64 different agencies.

One of the most prominent leaders in the halls of Congress, deeply concerned about the fuel/energy situation, is Senator Henry M. Jackson (D-Wash.), chairman of the Senate Committee on Interior and Insular Affairs. On April 10, Jackson's committee released a staff analysis entitled *Federal Energy Organization,* prepared for the Senate National Fuels and Energy Policy Study. We shall explore the substance of that report, as well as some inputs from Congressman Mike McCormack (D-Mass.), Jackson's opposite number in the House, and others expressing the Federal government viewpoint.

Facts come with blunt words

Sen. Jackson is considered by many—both inside and outside of Government—to be the most informed and open-minded man in Washington on the subject of energy. Thus, he may be taken seriously and literally when he recently stated that the most difficult problem facing the U.S. today is the energy crisis.

For United States citizens who have come to view defense, Vietnam, balance of payments, or a host of other ills as having top priority, Jackson's statement probably registered some incredulous reactions. Nevertheless, a very powerful case can be made for its preeminence, because the solution to the energy crisis may be the key to resolving many of our political and economic problems.

In the *Federal Energy Organization* report's "Memorandum of the Chairman," Jackson has this to say:

The well-publicized deficiencies of Federal organization in the energy field have become increasingly apparent in the course of the . . . study authorized by the 92nd Congress. Whether the subject is oil import policy, energy-resource management, or R&D programs, the lack of adequate authority and proper coordination is all too clear. And while no one suggests that better organization by itself will solve our energy problems, there appears to be general agreement that a revamped and strengthened energy organization is a necessary event to more rational energy policies.

The 93rd Congress must give priority to organizational issues as it deals with a broad range of energy problems. Recognizing this . . . I have asked that this memorandum be published at this time as background for the use of this and other Committees which have responsibilities in the field of energy organization.

Too many fingers in the energy pie?

The thrust of the Jackson committee report hinges on the contention that the 64 agencies either administering programs or implementing policies with specific impact on the energy system, make efficient planning almost impossible.

Tabulation of Federal energy agencies. Tables I and II list the Federal agencies found by Jackson's

1. Federal agencies that administer energy, policy or programs (Category A)*

Agency	Classification						
	1	2	3	4	5	6	7
Executive office of the President							
Domestic Council	A.1.a.c						
Office of Emergency Preparedness	A.1.a.b., A.2.a.b.c	X		X	X		X
Office of Management and Budget:							X
Natural Resources Programs Division	A.1.a.b.c						
Office of Science and Technology	A.1.a.; A.2.d	X		X			X
Federal Council for Science and Technology	A.1.a.; A.2.d			X			
Oil Policy Committee	A.1.a.b.						
Oil Import Appeals Board	A.2.c						
Joint Board on Fuel Supply and Transport	A.1.a						
Department of Agriculture:							
Forest Service	A.2.b				X		X
Rural Electrification Administration	A.2.a	X	X		X		
Department of Commerce					X		
Bureau of Domestic Commerce	A.1.a.; A.2.d.; B.2.d			X			X
Office of Import Programs	A.1.a.; A.2.c	X					
Department of Defense		X	X		X		X
Army—Corps of Engineers—civil	A.1.a.; A.2.a.b.c						X
Office of Naval Petroleum and Oil Shale Reserves	A.1.a.b.; A.2.b.c.d						X
Department of the Interior:							
Alaska Power Administration	A.1.a.b.c.; A.2.a.b.d	X			X		
Bonneville Power Administration	A.1.a.b.c.; A.2.a.b.d	X	X	X	X		
Bureau of Land Management	A.1.a.b.c.; A.2.a.b.c	X		X	X		X
Bureau of Mines	A.1.a.b.c.; A.2.a.b.c	X	X	X	X		X
Bureau of Reclamation	A.1.a.b.c.; A.2.a.b.c	X	X	X	X		
Defense Electric Power Administration	A.1.a	X		X	X		
Geological Survey	A.1.c.; A.2.d	X	X	X	X	X	X
Office of Coal Research	A.1.a.; A.2.d	X	X	X	X		
Office of Oil and Gas	A.1.a.; A.2.d	X	X	X	X		X
Oil Import Administration	A.1.a.b.; A.2.c	X	X		X		X
Southeastern Power Administration	A.1.a.b.; A.2.a.b	X	X		X		
Southwestern Power Administration	A.1.a.b.; A.2.a.b	X	X	X	X		
Department of Justice				X		X	
Land and Natural Resources Division	A.1.c.; A.2.c						X
Antitrust Division	A.1.a.; B.2.c						X
Department of State		X			X		
Office of Fuels and Energy	A.1.b.; A.2.d						X
Department of Transportation					X		
Office of the Secretary (grants-in-aid for natural gas pipeline safety)	A.2.a						
Federal Highway Administration (use of trust fund derived from energy tax)	A.1.b.; B.1.a.c.; B.2.a.b.d.						
Department of the Treasury				X	X		X
General Counsel	A.1.a						
Atomic Energy Commission	A.1.a.b.c.; A.2.a.b.c.d	X	X	X	X		
Environmental Protection Agency					X		X
Office of Air Programs	A.1.a.b.c.; A.2.c.d	X		X		X	
Office of Radiation Programs	A.1.a.b.c.; A.2.c.d	X				X	
Office of Solid Waste Management Programs	A.1.a.; A.2.a.b.d	X				X	
Federal Maritime Commission (oil pollution financial responsibility)	A.1.b.; A.2.c						
Federal Power Commission	A.1.a.b.c.; A.2.b.c.d	X	X	X	X		X
Federal Trade Commission	A.2.c	X			X		
General Services Administration					X		X
Federal Supply Service	A.1.b.; A.2.a.c.d						
National Aeronautics and Space Administration		X				X	
Space and Power Program	A.2.d						
National Science Foundation	A.1.a.; A.2.d	X					
Securities and Exchange Commission	A.1.b.; A.2.c					X	X
Small Business Administration	A.1.b.; A.2.a					X	
Tennessee Valley Authority	A.1.a.b.c.; A.2.a.b.c.d	X	X	X	X		
Water Resources Council	A.1.a.; A.2.d						

Notes:

Col. 1: Agency was classified as an energy agency in an independent survey made by the committee staff from available sources.
Col. 2: Agency responded affirmatively to questionnaire concerning fuels and energy goals.
Col. 3: Agency was determined to have energy related programs in an analysis made in 1968.
Col. 4: Agency was reported to have prepared or contracted for energy related studies.
Col. 5: Agency claimed direct statutory authority in the energy field.
Col. 6: Agency claimed indirect statutory authority in the energy field.
Col. 7: Agency was listed in a 1971 compilation of agencies [illegible] with oil and gas matters prepared by the Office of Oil and Gas.
* Agencies that administer programs [illegible] policies that have been specifically initiated for their particular impacts upon the U.S. energy system.

II. Federal agencies that administer energy policy or programs (Category B)*

Agency	Classification 1	2	3	4	5	6	7
Executive Office of the President:							
Council on Environmental Quality	B.1.a.b.c	X		X	X		X
Office of Management and Budget							
Budget Review Division	B.1.a.b.c						
President's Panel on Oil Spills	B.1.			X			
President's Task Force on Air Pollution	B.1			X			
Department of Commerce					X	X	
Bureau of Census	B.2.d	X					X
Maritime Administration	B.2.a						X
Department of Defense					X	X	
Defense Supply Agency, Central Supply and Maintenance	B.2.a.b.d						X
Department of Housing and Urban Development:							
Department participation in Urban Transportation R&D	B.2.d						
Department of the Interior:							
Bureau of Indian Affairs	B.2.b	X			X		X
Department of Transportation					X		
Office of the Secretary—Transportation Planning R&D	B.1.a.; B.2.d						
Coast Guard (oil pollution)	B.1.b.; B.2.a.c.d						X
Urban Mass Transportation Administration	B.2.d						
Department of the Treasury				X	X		
Internal Revenue Service	B.1.b.c.; B.2.c				X		
Civil Aeronautics Board (subsidy of Air service)	B.2.a						
Environmental Protection Agency:							
Office of Water Programs	B.1.a.b.c.; B.2.c.d	X				X	
Interstate Commerce Commission	B.1.b.; B.2.c				X		X
National Aeronautics Space Administration						X	
Office of Applications	B.2.d						
National Water Commission	B.1.a.c						

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Col. 6: Agency claimed indirect statutory authority in the energy field.
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[*] Agencies that administer programs or develop or implement policies that were not specifically intended to have unique impacts upon the energy system but that have proven in practice to have influences upon the energy system that are significantly different than the influences they have on other industrial or social systems.

committee to have specific energy policy roles. Table I includes agencies that administer the specific programs defined in the table's footnote. Table II includes agencies that administer policies or programs that are not specifically "energy oriented," but have unique impacts on the energy system.

Each table is coded to show the types of energy policy activities performed. The alphanumeric coding listed under "Classification 1" follows—

A. Specific energy activities (Table I)
  1. Policy formation
    (a) Planning and forecasting
    (b) Formation of standards, rules, regulations, and rates
    (c) Preparation or review of proposed legislation
  2. Policy implementation
    (a) Operations of energy facilities or production or marketing of energy or energy resources
    (b) Management of energy resources (including purchasing in quantities large enough to effect regional or national supplies)
    (c) Enforcement of rules and regulations
    (d) R&D, data collection, and technical assistance
B. Activities having unique impacts upon the energy system (Table II)
  1. Policy formation
    (a) Planning and forecasting
    (b) Formulation of standards, rules, regulations, and rates
    (c) Preparation or review of proposed legislation
  2. Policy implementations
    (a) Operation of facilities or production of resources having unique impacts upon the energy system
    (b) Management of resources
    (c) Enforcement of rules and regulations
    (d) R&D, data collection, and technical assistance

Proposed Federal reorganizations for energy

In this category of constructive recommendations, Sen. Jackson's committee report listed (1) *high-level surveillance of energy systems and provision for policy advice,* (2) *coordination and augmentation of Federal* *operating programs*, (3) *energy data collection, analyses and dissemination*, and (4) *coordination and augmentation of federal regulatory functions*. (We shall discuss items 1, 2, and 4 in more detail.)

High-level surveillance. Sen. Jackson introduced the *National Resources Planning and Policy Act of 1972* for the purpose of improving the organization, policy-making, planning, and management of our natural resources to meet a new national goal. The act would be concerned with the development of new technologies, better monitoring and data collection, research on new methods to produce more efficient and cleaner energy sources, and better decision-making and coordination of activities within the Federal government.

The proposed Board on Natural Resources Planning and Policy would have three members whose duties would include

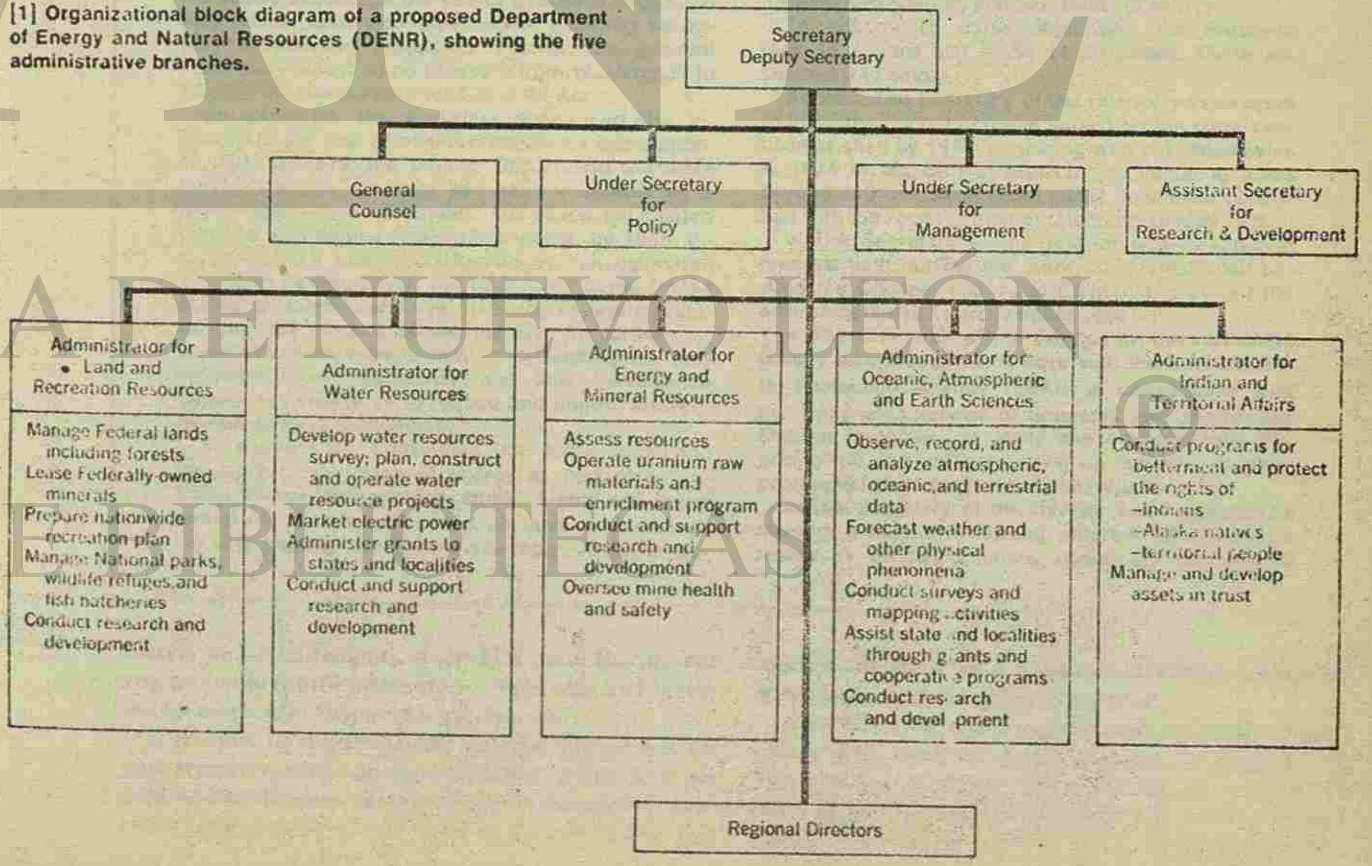
- The coordination and improvement of all Federal programs and activities in the natural resources and energy fields.
- Conducting of studies and research.
- The responsibility, where appropriate, to ensure that technical and economic information accompanies environmental impact statements.
- The recommendation of policy changes and new programs or actions.
- The recommendation, jointly with the Council on Environmental Quality, of alternatives to Federal actions enjoined by the courts.

One of the most important assignments of the Board would be the preparation and transmittal to Congress of an annual "natural resources report." This report would meet the need for a continuing assessment of present and projected natural resources requirements, R&D efforts, data-collection and monitoring activities, etc. With this information base and annual assessment of problems, Sen. Jackson believes both Congress and the Executive Branch would be greatly assisted in the preparation and implementation of needed policies for the management, conservation, use, and development of fuel resources.

Council on Energy Policy (House and Senate bills). This proposal would, in general, create such a Council within the Executive Office of the President for the purposes of establishing a central point for the collection, analysis, and interpretation of energy statistics and data to assist in securing policies "for wise energy management and to anticipate social, environmental, and economic problems associated with existing and emerging technologies." The Council would also coordinate all energy activities of the Federal government and prepare a long-range comprehensive plan for energy utilization "to foster improvement of the efficiency of energy production and utilization . . . and the conservation of energy resources by reducing energy demands . . . ."

National Energy Advisory Board. Another proposal is the establishment of a National Energy Resources Advisory Board as an independent agency in the Executive Branch. Its functions would be to

1. Make a full investigation, on a continuing basis, of the current and prospective fuel and energy re-



[1] Organizational block diagram of a proposed Department of Energy and Natural Resources (DENR), showing the five administrative branches.

Highlights of the President's message on energy

Of the actions and proposals included in President Nixon's message on energy, sent to the Congress on April 18, and also directed to consumers and industry, the principal executive action disclosed was the termination of oil import quotas. Mr. Nixon announced that the 14-year-old quotas would be replaced by a license fee applied to all oil and gas imports. This action, which was first recommended in 1970 by a Presidential panel commissioned to consider the energy picture in the U.S. (but was subsequently ignored by the President), will serve to ease temporarily oil shortages that have resulted from the rapid depletion of U.S. oil reserves. But to avoid increasing our balance-of-trade deficits—and becoming subject to the whims of the governments of oil-producing nations—Mr. Nixon proposed several additional programs to Congress:

He urged Congress to terminate Federal regulation of wellhead prices of natural gas, our cleanest fuel, as an incentive to exploration. Newly discovered wells and those newly dedicated to interstate markets would be freed of the Federal Power Commission's jurisdiction immediately, and those wells already producing would become free when their present contracts expired. According to the President, "ill-conceived regulation" has served only to keep prices low for "America's premium fuel," but as a direct consequence, industries and utilities have neglected oil and coal—which is less used than other fuels but abundant—thereby depleting natural gas wells faster than new ones can be developed.

In this connection, the President advised Congress to authorize an additional tax subsidy in the form of a tax credit to encourage the oil industry to increase exploration outlays. Further, he urged the Interior Department to authorize the licensing of deepwater offshore tanker terminals. This, he expected, would decrease pollution through the utilization of "fewer but larger" tankers.

In his message, Mr. Nixon also recommended that the states encourage the use of coal, and suggested they might "take their time" about effecting secondary air-pollution standards. Further, he assured them there would be no pressure from Washington to enforce the standards of the Clean Air Act.

As expected, the President announced the increase of the sale of offshore leases for exploration, so that, by 1979, the Interior Department will triple leased acreage. In what has been described as a highly speculative statement, Mr. Nixon anticipated that the accelerated leasing rate could, by 1985, increase annual energy production by "an estimated 1.5 billion barrels of oil" (or 16 percent of the United States' oil needs), and five trillion cubic feet of natural gas (20 percent of the needs). He further assured environmentalists that "new techniques, new regulations and standards, and new surveillance capabilities enable us to reduce and control environmental dangers substantially."

To workers and consumers, Mr. Nixon urged the voluntary conservation of energy as part of a "national energy conservation ethic." Lights are to be turned off, automobiles tuned up, and air-conditioning and heating used more sparingly. Also, he announced the establishment of an Office of Energy Conservation in the Department of the Interior "to educate consumers" by, among other means, labeling products for their relative efficiency of energy use.

Mr. Nixon reaffirmed his commitment to nuclear power-plant development, speaking of producing half the country's electric energy by this means by the year 2000, and promising to propose methods to shorten the time-consuming licensing procedures that have delayed such plants.

Finally, the President reiterated his commitment to early construction of an Alaskan oil pipeline and reviewed the 20 percent increase in Federal funding of R&D programs proposed in the January budget. Although he was enthusiastic about the potential of oil-shale reserves and the harnessing of geothermal energy, he reserved judgment on these programs pending further information. He did, however, direct the Department of the Interior to prepare a leasing program for the development of geothermal energy on Federal lands.

In summary, President Nixon's message to Congress attempted to define a national energy policy. As he saw it, such a policy must have six objectives:

- To reduce excessive regulatory and administrative impediments that have delayed or prevented construction of energy-producing facilities.
- To increase domestic production of all forms of energy.
- To act to conserve energy more effectively.
- To strive to meet our energy needs at the lowest cost consistent with the protection of both our national security and our natural environment.
- To act in concert with other nations to conduct research in the energy field and to find ways to prevent serious shortages.
- To apply our vast scientific and technological capacities—both public and private—so we can utilize our current energy resources more wisely and develop new sources and new forms of energy.

To accomplish these objectives, the President took 16 actions and made 14 proposals. These are summarized below:

Actions. The Secretary of the Interior was directed to triple the annual acreage leased on the outer continental shelf by 1979, beginning with expanded sales in 1974 in the Gulf of Mexico and including areas beyond 200 meters in depth under conditions consistent with the "oceans policy statement" of May 1970.

- The Secretary of the Interior was directed to proceed with leasing the outer continental shelf beyond the Channel Islands of California, provided the environmental risks prove acceptable.
- The Chairman of the Council on Environmental Quality was requested to work with the Environmental Protection Agency (EPA), in consultation with the National Academy of Sciences and appropriate Federal agencies, to study the environmental impact of oil and gas production on the Atlantic outer continental shelf and in the Gulf of Alaska.
- The Secretary of the Interior was requested to develop a long-term leasing program for *all* energy resources on public lands, based on the nation's

sources and requirements of the U.S., and the present and probable future alternative procedures and methods for meeting anticipated requirements.

2. Submit to the President and the Congress a report recommending specific legislative action with regard to coordination of effective and reasonable policies to ensure reliable and efficient sources of fuel and energy adequate for a balanced economy, a clean environment, and the national security.

Coordination and augmentation of Federal operating programs. A major proposal in this category has emanated directly from President Nixon rather than from the Senate committee. This is the President's proposal for a Department of Energy and Natenergy, environmental, and economic objectives.

- The Department of the Interior was directed to institute a new reporting system on national coal production and the FPC is to report regularly on the use of coal by utilities.
- The spending of R&D in coal, with special emphasis on technology for sulfur removal and the development of low-cost, clean-burning forms of coal, is to be stepped up.
- Legislation is to be resubmitted to Congress this year, with a number of new provisions to simplify licensing of nuclear plants and requiring that the Government act on all completed license applications within 18 months after they are received.
- By proclamation, all existing tariffs on imported crude oil and products are to be removed, and holders of import licenses will be able to import petroleum duty free.
- Direct control over the quantity of crude oil and refined products that can be imported has been suspended and will be replaced by a license-fee quota system.
- An Office of Energy Conservation is to be established in the Department of the Interior to coordinate the energy-conservation programs that have been scattered throughout the Federal establishment, to conduct research, and to cooperate with consumer and environmental groups in efforts to educate consumers in energy efficiency.
- The Department of Commerce, working with the Council on Environmental Quality and the EPA, was directed to develop a voluntary system of energy efficiency labels for major home appliances to assist the consumer further.
- The Department of State, in coordination with the AEC, other Government agencies, and the Congress, was instructed to move rapidly in developing a program of international cooperation—such as the joint research presently being pursued in MHD by the U.S. and the Soviet Union—in R&D of new forms of energy and in developing international mechanisms for dealing with energy crises.
- A new post has been created, that of Counselor to the President on Natural Resources, to assist in the policy coordination in this area.
- The Secretary of the Interior was directed to strengthen his departmental organization of energy activities in the following ways: the responsibilities of the new Assistant Secretary for Energy and Minerals will be expanded to incorporate all departmental energy activities; the Department is to develop a capacity for gathering and analyzing energy data; an Office of Energy Conservation is being created to seek means for reducing energy demands; and the Department has also strengthened its capabilities for overseeing and coordinating a broader range of energy R&D.
- By Executive order, the Department of the Treasury was authorized to direct the Oil Policy Committee that coordinates the oil import program.
- By a second Executive order, a special energy committee, composed of three of the President's principal advisors, was established to deal with top-level energy policy matter and a new division of Energy and Science was established within the Office of Management and Budget.

Proposals. Gas from new wells, or gas newly dedicated to interstate markets, and the continuing production of natural gas from expired contracts should no longer be subject to price regulation at the wellhead.

- The Secretary of the Interior should be authorized to impose a ceiling on the price of new natural gas when circumstances warrant.
- Congress should pass legislation providing appropriate settlements for those forced to relinquish Santa Barbara Channel leases in 1971.
- Congress should act swiftly so that we can expedite the construction of the Alaska pipeline.
- The highest national priority should be given to expand development and utilization of our coal resources.
- Strong legislation should be enacted as soon as possible to protect the environment from abuse caused by strip mining.
- All state utility commissions should ensure that utilities receive a rapid and fair return on pollution-control equipment, including stack-gas-cleaning devices and coal-gasification processes.
- Siting legislation should be enacted by Congress for electric generating facilities and for deep-water ports to accommodate "supertankers."
- Congress should extend the investment credit provisions of our present tax law to encourage exploratory drilling for new oil and gas fields.
- Legislation should be enacted to permit the Department of the Interior to issue licenses for deep-water ports.
- Local officials should be permitted to use money from Highway Trust Funds for mass-transit purposes.
- The following provisions in the Presidential budget for fiscal 1974 should be approved: a 20 percent increase in energy R&D funding; the creation of a new central energy fund in the Interior Department to provide additional money for nonnuclear R&D (most particularly coal research); a 27 percent increase in coal R&D; increased funding of R&D for the liquid metal fast-breeder reactor, reactor safety and radioactive waste disposal, and the production of nuclear fuel; a 35 percent increase in funding for our total fusion R&D effort and the initiation of reactor design studies; additional funds to assure reactor safety; the tripling of our solar energy R&D; and a 24 percent increase of R&D funds relating to environmental control technologies.
- All state utility commissions should review their regulations regarding R&D expenditures to assist the electric utility industry in its R&D efforts.
- Legislation should be enacted to consolidate Federal energy-related activities within a new Department of Energy and Natural Resources (DENR), which would build on the already proposed legislation, with heightened emphasis on energy programs, and "would provide leadership across the entire range of national energy. It would, in short, be responsible for administering the national energy policy detailed in this message."

ural Resources (DENR)—previously referred to as the Department of Natural Resources (DNR)—which would combine policy making and operations for energy R&D. The DENR would comprise five major administrations, one of which would be for energy and mineral resources. Concerning DENR, Mr. Nixon said:

"... A new Department of [Energy and] Natural Resources should be created that would bring together the many natural resource responsibilities now scattered throughout the Federal government. This department would work to conserve, manage and utilize our resources in a way that would protect the quality of the environment and achieve a true harm-

Reactions to the Nixon message

As might be expected, depending on the source, reactions on the President's message on energy varied. Many Congressional experts on our energy outlook believe that Mr. Nixon's measures come at least six years too late. Laying at the doorstep of the Johnson Administration the responsibility for the original failure to establish a national energy policy before what they believe to be crisis conditions that obligated President Nixon to act, this critical group further maintains that it will take several years to effect the Nixon proposals, even presuming he can obtain Congressional approval—a doubtful prospect considering the stiff opposition he faces from a Democrat-controlled Congress.

On the other hand, the Nixon message met with a generally favorable, though guarded, reaction from the energy industry, and *Spectrum* found oil industry spokesmen felt similarly. The latter view the present situation as a "crunch" of short-term duration rather than as a full-blown crisis, and they go along with such proposals as:

- Removing natural gas prices from regulation.
- Removing oil-import quotas.
- Expanding the leasing of offshore oil and gas sites.
- Postponing national air-quality standards.

Said John G. McLean, chairman of the Continental Oil Company and head of the National Petroleum Council, to *Spectrum:* "We must take all necessary steps to stimulate the development of our indigenous energy resources."

Among such steps, Mr. McLean told *Spectrum* he favors strengthened tax incentives for the development of energy resources and "reasonable modifications in the ecological constraints that are, at present, inhibiting the development and consumption of our indigenous fuels."

But Arnold R. Miller, president of the United Mine Workers UMW, reacted with considerably less enthusiasm to Mr. Nixon's message, expressing to *Spectrum* the UMW's feeling that "we face an emergency situation today because Government has failed to develop a national approach to our energy needs, but, instead, has permitted corporate interests to develop and supply the nation's energy in accordance with their profit instincts alone."

Furthermore, no one in the Administration consulted with the leaders of the 200 000-man UMW on energy policy decisions, Mr. Miller pointed out, and he went on to say that "there has been no indication from the Administration of any concern that thousands of miners may lose their jobs." By this, Mr. Miller is expressing the UMW concern that the shift from deep-mining of high-sulfur-content coal in the Appalachian states to strip-mining of low-sulfur coal in the West may lead to the abandonment of important coal mining east of the Mississippi River.

Finally, Mr. Miller blamed industry and Government "myopia" for the slow development of sulfur-removal processes that would preserve the Appalachian coal economy.

And as for the environmentalists and those concerned with conservation, they, too, found the President's message in conflict with their interests, charging that the proposals favored economic over ecological concerns.

ony between man and nature . . . .

The new Department of [Energy and] Natural Resources would absorb the present Department of the Interior . . . ."

The bill to accomplish the creation of the DENR was introduced into the House of Representatives by Congressman Chet Holifield (D-Calif.). Proposed within the DENR is an Energy and Mineral Resources Admintration, headed by an administrator who would report to the Secretary. Figure 1 represents an organizational block diagram and shows the five administrations within the DENR.

Coordination and augmentation of Federal regulatory functions. Two major proposals that address this topic are the Ash Council recommendations and a study by the Bar of the City of New York:

Ash Council report on independent regulatory agencies. The President's Advisory Council on Executive Organization (Ash Council) submitted its report on the independent regulatory agencies to Mr. Nixon on January 30, 1971. The recommendations, however, were not submitted to Congress. The report made several far-reaching suggestions for restructuring the various commissions—including the FPC—that included the abolition of these agencies *per se.* The functions of these agencies would be headed by a single administrator of a supra-agency appointed by and serving at the pleasure of the President (following confirmation by the Chief Executive). Included in this supra-agency would be a newly established Federal Power Agency.

The report also recommended the streamlining of the adjudicative processes of the regulatory functions by restricting review of hearing examiner decisions so that "hearing examiners would enjoy the status of administrative judicial officers." Appeals from the Federal Power Agency's final judgment, for example, would be taken to a new Administrative Court, with appeal only to the U.S. Supreme Court.

Report of Special Committee on Electric Power and the Environment, New York City Bar. This special committee was the outgrowth of four regular committees dealing with power plant siting in New York State. The committee transmitted its final report in August 1972 and, although its focus was not on Federal reorganization, it made recommendations for reform of the Federal regulatory framework.

For example, the report recommends the creation of an "Energy Commission" that would be a regulatory body "consolidating the regulatory duties of the FPC, AEC and, preferably, those parts of the Federal government dealing with energy forms other than electricity," and an "Energy Agency" that would be "a developmental body consolidating the research activities of the AEC, Office of Coal Research, and all other administrative and executive offices concerned with energy R&D."

Further, the Energy Commission would have the responsibility for studying the extent to which the demand for energy should be encouraged or discouraged, and then presenting its recommendations to Congress. The commission would also be charged with reviewing the intermediate-range plans of utilities and determining how much new generating capacity is

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- Removing natural gas prices from regulation.
- Removing oil-import quotas.
- Expanding the leasing of offshore oil and gas sites.
- Postponing national air-quality standards.

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ony between man and nature . . . .

The new Department of [Energy and] Natural Resources would absorb the present Department of the Interior . . . ."

The bill to accomplish the creation of the DENR was introduced into the House of Representatives by Congressman Chet Holifield (D-Calif.). Proposed within the DENR is an Energy and Mineral Resources Admintration, headed by an administrator who would report to the Secretary. Figure 1 represents an organizational block diagram and shows the five administrations within the DENR.

Coordination and augmentation of Federal regulatory functions. Two major proposals that address this topic are the Ash Council recommendations and a study by the Bar of the City of New York:

Ash Council report on independent regulatory agencies. The President's Advisory Council on Executive Organization (Ash Council) submitted its report on the independent regulatory agencies to Mr. Nixon on January 30, 1971. The recommendations, however, were not submitted to Congress. The report made several far-reaching suggestions for restructuring the various commissions—including the FPC—that included the abolition of these agencies *per se*. The functions of these agencies would be headed by a single administrator of a supra-agency appointed by and serving at the pleasure of the President (following confirmation by the Chief Executive). Included in this supra-agency would be a newly established Federal Power Agency.

The report also recommended the streamlining of the adjudicative processes of the regulatory functions by restricting review of hearing examiner decisions so that "hearing examiners would enjoy the status of administrative judicial officers." Appeals from the Federal Power Agency's final judgment, for example, would be taken to a new Administrative Court, with appeal only to the U.S. Supreme Court.

Report of Special Committee on Electric Power and the Environment, New York City Bar. This special committee was the outgrowth of four regular committees dealing with power plant siting in New York State. The committee transmitted its final report in August 1972 and, although its focus was not on Federal reorganization, it made recommendations for reform of the Federal regulatory framework.

For example, the report recommends the creation of an "Energy Commission" that would be a regulatory body "consolidating the regulatory duties of the FPC, AEC and, preferably, those parts of the Federal government dealing with energy forms other than electricity," and an "Energy Agency" that would be "a developmental body consolidating the research activities of the AEC, Office of Coal Research, and all other administrative and executive offices concerned with energy R&D."

Further, the Energy Commission would have the responsibility for studying the extent to which the demand for energy should be encouraged or discouraged, and then presenting its recommendations to Congress. The commission would also be charged with reviewing the intermediate-range plans of utilities and determining how much new generating capacity is actually needed, as well as the general locations in which such new capacity should be sited.

Finally, the proposed Energy Agency is designed to be a "one-stop" regulatory framework for power plants and their licensing.

Inputs from the "House" side

Congressman McCormack, chairman of the Subcommittee on Energy of the House Committee on Science and Astronautics, made some cogent remarks before the National Conference of the Joint Engineering Legislative Forum last February 27. Commenting on the future of nuclear, solar, and geothermal energy, Mr. McCormack had this to say:

"The U.S. must depend heavily upon nuclear fission to ... meet its energy needs for the rest of this century. I hope the time will come, after 2000, when we can—as a matter of world policy—totally abandon the combustion of fossil fuels and the use of nuclear fission as sources of energy, and turn instead to the nearly inexhaustible ... and nonpolluting sources available to us in the future. Until that time, however, our only rational course is to proceed vigorously with our present programs—including the development of the LMFBR, and alternative breeder concepts . . . .

"One of the . . . inexhaustible and potentially nonpolluting sources is solar energy. . . .With adequate R&D support over the next 30 years, solar energy could provide at least 35 percent of the heating and cooling of future buildings, more than 30 percent of the methane and hydrogen needed in the U.S. for gaseous fuels, and more than 20 percent of the country's needs for electric power . . . .

"Several encouraging studies are underway, but a well-managed, progressive, imaginative program for solar energy should be established at once. It should set, as its immediate goal, a series of inexpensive and simple experiments to determine whether ... solar energy would provide the potential for ... central power stations that its advocates claim . . . . Solar energy, if it is economically feasible, would have a minimum impact upon the environment . . . . It is my hope that the Subcommittee on Energy . . . can work closely with the NSF, other Federal agencies, and private agencies to establish a program for solar energy research . . . Such a program should anticipate the extensive use of solar energy by the mid-1980s . . . .

"Geothermal may be another essentially inexhaustible energy source. Research ... indicates that the conversion of such energy would also be nonpolluting, with closed systems pumping exhausted steam or hot water back into the ground. The concept also considers the possibility of pumping seawater into the ground to produce dry steam to drive turbogenerators . . . But, as with solar energy, an organized program is required.

"Two 'far-out' sources of inexhaustible energy may be available to us: fusion, and satellite solar energy. I am encouraged with the programs on fusion research (although I suspect they are 'underfunded' by $5 to $7 million in the President's proposed budget for fiscal 1974). Fusion energy will not be pollution free. We can be sure that in the early generations of [such] power stations, we will have large amounts of waste heat released to the atmosphere [plus] radioactive materials—including small amounts of tritium . . . .

"Satellite solar energy can be considered to be pollution free, except for heat loss in converting microwaves to electric energy, and in use of the energy itself. It *does* involve many flights of the space shuttle and the use of a nuclear-powered transportation system from low to synchronous stationary orbit . . . .

"With regard to these 'exotic' sources, I hope that we may have a pilot nuclear fusion plant by the year 2000, and that it will prove to be economically competitive . . . ."

Other spokesmen, other views

Interior Secretary Rogers Morton has, for some time, been advocating the construction of the trans-Alaska pipeline. His position is now substantially reinforced by President Nixon's latest energy message. Nevertheless, the construction of this line will probably be delayed for a considerable time by the complexities of current court litigation initiated by conservationist groups to block the project. Morton's advocacy of the trans-Alaskan stems primarily from his reluctance to "find ourselves really in a position of total dependence on other parts of the world for our energy base." He feels this would place the U.S. in a "very insecure position."

Stewart Udall, Secretary of the Interior in the Kennedy and Johnson Administrations, feels that the best alternative to the crises is a conservation of both fuels and energy. He advocates smaller cars, commuter car pools, more dependence upon mass rapid transit, and barring private motor vehicles from the downtown areas of major cities. Udall tends to view the insatiable energy demand as a force that must be curbed and controlled if we are to conserve our natural resources and preserve the environment.

A concluding observation

Unfortunately, one "energy message" from the President will not "clear the air"—either environmentally or politically. The abrupt lifting of the oil import quotas may raise more questions and problems than it will solve, especially in the sensitive area of balance of payment deficits. Further, the politically unstable Middle East will be an important factor in the future unstable fuel equation.

As we go to press, Senator Jackson announced that his committee will hold hearings on coal policy issues, beginning June 6. Said Jackson: "Coal is a critical and vital element in the [U.S.] energy supply picture. Progress toward the goal of national energy self-sufficiency will depend . . . on our ability to use our vast coal resources more effectively and in environmentally acceptable ways . . . . We cannot ignore the fact that the production and use of coal has been seriously affected by government action . . . . Only a concerted effort by both Congress and the Executive branch will enable coal to achieve a greater role in meeting our future energy needs."

Jackson also released a background paper on "Factors Affecting the Use of Coal in Present and Future Energy Markets." The report identifies public policy issues affecting coal's future, describes the impact of present and proposed public policies on that fuel's economic position as an energy source, and suggests the potential of coal in meeting energy needs.

Oil: the omnipotent energy source

Between now and 1985, an adequate petroleum supply will be the 'hinge of fate' for the U.S. economy

Gordon D. Friedlander Senior Staff Writer

As early as 1970, Libyan President Muammar el-Qaddafi threatened to withhold oil from the U.S. in order to punish the U.S. Government for its Middle East policy. For some time, it has been apparent to Qaddafi that the future of the Middle East might be drastically altered in favor of the Arab states if only the oil-producing nations would unite behind a concerted policy tantamount to economic blackmail of the United States.

Until recently, however, there was no indication that Saudi Arabia, long the most conservative of the Arab governments and, significantly, the oil-richest of the Arab states, would participate in such a policy. Then, in an interview given in April in the U.S., the Saudi Arabian Minister of Petroleum Affairs, Sheik Ahmed Zaki al-Yamani said in no uncertain terms, "We are in the 'driver's' seat and can dictate prices; further, we shall become richer than ever before." Since his government is already accumulating revenues at the rate of $2.3 billion a year from its oil exports, it was no empty threat when he further warned that Saudi Arabia might not increase oil production "unless there was a change in the political climate."

Whether oil will be used as a "weapon" or "club" to force a reappraisal by the U.S. of its attitudes and political relationships toward other nations, time alone will tell. But in Western Europe, and especially in France and Italy where there is a heavy dependence on oil imports from Libya and the Middle East, the situation has already influenced the political climate and has been reflected by increased shipments of military arms to Arab nations. As one European oil company official commented bitterly, "when a handful of Bedouins in Libya can, by withholding their oil, paralyze the economy of an industrialized European country such as Italy, that is an absurd situation—but it is also a reality."

And since that statement, what amounts to the first test case of a political Arab monopoly was effected. In Beirut, Lebanon on May 15, four Arab countries (Libya, Iraq, Kuwait, and Algeria) got together to announce a temporary halt of their westward oil flow as a symbolic protest against the continued Western approbation (as they see it) of Israel's existence. Although the stoppage was to last only one hour (Libya shut her pumps for 24 hours), the possible future significance of the tactic is clear.

Since 1960, the domination of the world's oil supply has been shifting from the affluent oil-consuming industrial nations to the "underdeveloped" oil-producing countries. Since 1970, this dramatic shift was accelerated as increasing nationalism and threats of expropriation of foreign oil interests in the Middle East have forced a 60–70 percent increase of oil prices to the consumer nations over the past three years.

In the U.S., since oil will be the predominant energy fuel during the next 12 years (in fact, the only fuel capable of meeting our escalating energy requirements), the potentially adverse effects of Middle East manipulation of the oil flow on the balance-of-payments deficit, alone, are staggering.

The wealth of the Middle East

Figure 1 is a map of the seven major oil-producing nations of the Middle East. The callouts contain the populations of these countries (all relatively small compared with the huge populations of the industrial oil-consuming nations), and their oil revenues reported as of 1972. The expected revenues for 1973 will show marked increases in these figures. The table contained in the illustration indicates the proven reserves of each country and the present production in millions of barrels per day. Saudi Arabia has, by far, the largest underground reserves—some 145 billion barrels—which represents more petroleum than is contained in the United States and Latin America combined. And the "desert Kingdom" probably has much more oil still to be discovered.

Although the present Saudi production is set at about 6 million barrels per day, this quantity could be pushed upward to 20 to 30 million barrels per day by 1980. And, oddly enough, the latter figures represent the projected import requirements of the [illegible] and Japan (combined) as of that date.

The new order

The advantageous position of the Middle East's oil producers did not evolve overnight; slowly, but steadily, they are recovering control over their resources from Western nations. Historically, over the past 40 years, control was wielded by the major European and U.S. companies under long-term leasing concessions. Under the terms of these tradional concessions, the *companies* decided how much oil to produce, where it was to be sold, and for how much. Generally, the "host" government received a fixed royalty of about 12½ percent of the sale price, plus a tax that was set at about 50 percent of the net sales price (after the deduction of royalty and production costs).

It was almost predictable that such an arrangement would eventually lead to trouble—and it did, in 1960. Because oil supplies to the consuming nations were relatively plentiful at that time, small independent companies in the U.S. and elsewhere began a "price war" and sold petroleum products below the prices established by the major firms. The big companies reacted by also declaring a price reduction. Because the taxes of the Middle East nations were based on the posted prices, the price war resulted in a reduction of government revenues for the host countries. Although the producing nations protested the action, the foreign oil concessionaires insisted on their prerogative and right to set prices. The reaction to this was that Saudi Arabia, Iraq, Iran, Kuwait, and Venezuela established the Organization of Petroleum-Exporting Countries in 1960. At first, they tried to reinstate the 1960 posted prices, but their organization proved ineffective. It was not until the Arab-Israeli war of 1967, which resulted in the closing of the Suez Canal, that the bargaining position of the host nations improved.*

Thus, by 1969, the five-nation organization began a concerted attack on the concession system and established the right of the producing countries to fix prices and regain partial or full ownership of petroleum resources by means of participation agreements or expropriation.

Deep water or deep trouble?

The immediate problem confronting the U.S. is in part a matter of logistics; it must develop new oil sources, construct refineries within its continental borders, and establish conservation policies that will mitigate the coming crunch. But, at the present time, it does not seem likely that such a large order can be filled.

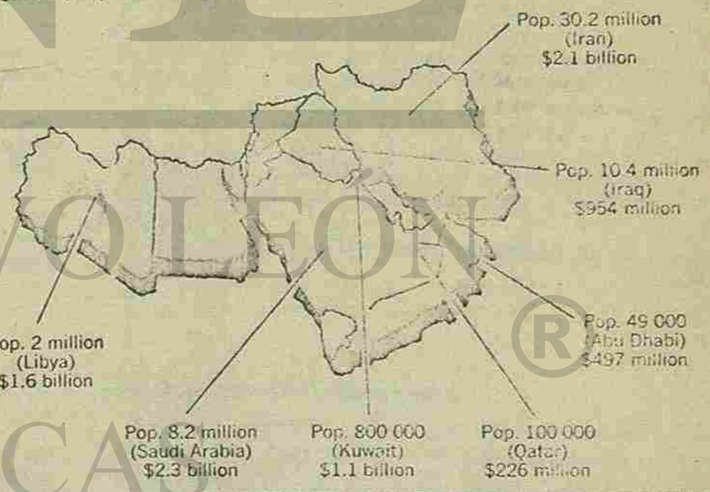
As of now, (for reasons indicated in our introductory article—see the May issue of *IEEE Spectrum*), not a single new oil refinery is being built in the U.S. But in addition to the lack of sufficient oil-refining capacity in the U.S., there is a major impediment that is blocking bulk imports of petroleum: lack of deep-water facilities. Since the closing of the Suez Canal in 1967, oil tankers have grown in size from about 50 000 deadweight tonnes to 250 000 tonnes (and Japanese builders are constructing vessels of up to 500 000 deadweight tonnes). Unfortunately, however, there is not one port in the U.S. that can accommodate a loaded tanker of more than 120 000 tonnes. (A proposed offshore loading facility off the coast of Maine has run into heavy flak from conservationists.)

The cascading shortages

In the introductory article in the series (May), we discussed the dwindling supplies of petroleum distillate and natural gas that beset much of the U.S. heartland this past winter. Since that writing, we have been warned of an impending dearth of gasoline this summer, that those vacationing by automobile may be in for some unpleasant surprises at filling stations whose supplies are exhausted, and that gasoline rationing in some form may be the next unpalatable measure. Already many independent stations have been literally forced out of business. Meanwhile, automobile production and sales are at a record high, and the industry reports indicate that more than 9 million motor vehicles came off the assembly lines in the past year.

Furthermore, U.S. autos are getting less economical to operate, with more power options, higher horsepower, lower compression ratios (and hence decreased efficiency), while gas consumption in these outsized jalopies has increased markedly. So the day may not be far off when John Q. Public buys his gleaming Jazzmobile Super-8, with a $6000 price tag, and then finds he cannot fill his 30-gallon tank with that stuff

[1] Oil in the Middle East. In an area of relatively small populations, huge oil reserves are found. The oil production figures (in quantities and revenues) are based on 1972.



Oil production and reserves in area

	Millions of barrels a day	Proven reserves (in billions of barrels)
Saudi Arabia	6.0	145.0
Kuwait	3.3	66.0
Iran	5.0	55.5
Iraq	1.4	36.0
Libya	2.2	25.0
Abu Dhabi	1.0	18.9
Qatar	0.48	6.0

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*The closing of the Suez Canal led to the construction of the "supertankers"—vessels of 200 000-500 000 deadweight tonnes—that bypass the canal and deliver many times the amounts of oil that could be carried in conventional smaller tankers. Thus, the value of the Suez Canal as a strategic waterway has been greatly diminished and, today, is largely obsolete; the supertankers are too large and too deep of draft to negotiate that waterway. Also, the 1967 war spurred the consideration of more pipelines directly to Mediterranean and Red Sea ports for trans-shipment by sea.

Keeping the 'energy' peace

Last February 5, Thornton F. Bradshaw, president of the Atlantic Richfield Company, presented his philosophy (under the title of the above subhead) on the energy crisis at the European Investment Seminar in Paris. The following are pertinent excerpts from his speech—

As inhabitants of . . . earth, we face together a far broader challenge: how do we ensure a flow of vital energy to all nations . . . without sowing the seeds of discord, without pitting producing nations against developing nations. I do believe that an inadequate flow of energy . . . can provide more discord among nations than all the ideological struggles of the past and present.

The supply of hydrocarbons—oil, gas, coal—is limited . . . and the hydrocarbon age . . . is finite in time [but] we are bound to hydrocarbons for the next 30 or 40 years.

The major deposits of hydrocarbons are concentrated in a few, relatively underdeveloped nations. The large industrialized nations, whose life depends upon a flow of hydrocarbons . . . do not have adequate sources of supply within their own borders.

The one exception to this imbalanced situation has been the United States. For many years, the U.S. was a surplus nation. Not only did it have oil to fuel the appetite of its industrial society—and the appetite has been voracious—but in times of crisis it was able to come to the support of other nations. The presence of surplus oil in the U.S. provided a balance of power which served to maintain an "energy peace." This is no longer so. The U.S. is now a "have not" nation in energy. It can no longer keep the energy peace. It must now queue up for energy supplies along with other industrialized nations . . .

In 1965, the U.S. consumed nearly 12 million barrels of oil a day; produced 9 million barrels; imported 2½ million barrels—and had 3 million barrels a day spare producing capacity.

In 1972, the U.S. consumed more than 16 million barrels a day; produced over 11 million barrels, and imported about 4½ million barrels a day. There was no spare capacity.

By 1985, we anticipate [the] U.S. demand will be more than 25 million barrels a day; productive capacity will be less than 12 million barrels, and we probably will be importing . . . 13 to 14 million barrels a day.

What happened? Have we run out of hydrocarbon resources? The answer is no, but we have run out of the ability to produce these resources now and for a significant span of time in the future . . .

Does this sound like a nation which has run out of energy resources? Not at all. It is a nation, however, which made a series of ad hoc policy decisions [that] has created an untenable situation—energy riches beneath the ground, energy poverty above the ground . . .

Environmental conflicts have delayed the building of refineries. Refineries are now operating near capacity, and there are none being built. Attempts have been made to build refineries on the East Coast of the U.S.; all have been blocked by action of environmentally oriented groups and by inadequate market prices. We estimate that seven new refineries will be needed on the East Coast by 1975. They will not be there.

There is a solution to all this, and I am hopeful that [it] will be forthcoming shortly. I am hopeful that the events of this past winter—the oil shortages in the U.S.; the actions of the Middle Eastern nations, which . . . will pass control of most of the world's oil to those nations during this decade; the realization of the . . . changed position of the U.S., that all these things—will spur our government to create an effective national energy policy . . .

I recognize that the President has to call upon experts from all parts of the government to provide him with the material for an effective national energy policy. I have been carrying around the elements of such a policy in my head for a long time. If he wished to save time and expense he could call on me. This would be my energy policy:

1. Remove constraints from gas pricing. This would permit the price of [natural] gas to reflect its high value as a clean, attractive fuel. Such a price would discourage uneconomic use . . . [and] would also bring forth the risk capital . . . to search out and bring to the surface the 700 trillion cubic feet, which geologists say are waiting to be discovered.

2. Permit the price of crude oil and products to rise to the point that capital would . . . provide the means of finding and tapping the 100 billion barrels which still await us.

3. For many reasons of security and national economic interest, an energy policy should include incentives to prevent exporting refineries to offshore sites . . .

4. There should be a mechanism developed for resolving environmental conflicts. Environmental . . . points of view should be brought to bear on each major project . . . for a finite period of time. Once this process has run its course, there must be a mechanism for making a decision in the public interest . . .

5. An energy policy must also provide for increased long-range R&D directed at both the uses of hydrocarbons and the [alternative] forms of energy to come . . .

6. Get the North Slope crude oil flowing to the market . . . .

the British, quite logically, call "petrol."

The United States evolved into a superstate on a diet of inexpensive and bountiful indigenous energy resources, and nobody in the country (until recently) has winced at the fact that, with 6 percent of the world's population, his nation accounts for one third of the world's energy consumption. Unhappily, affluence, and the expectation of abundance in everything breed complacency and a taken-for-granted self assurance. Thus, a traumatic and near-term *future shock* will probably occur when the long-term Cadillac customer is suddenly informed that there will be hardly enough gas available for him to drive a VW, and that he *really* should rely more on mass transit.

Of supply, demand, and reserves

John G. McLean, chairman of Continental Oil Company and head of the National Petroleum Council contends that, in terms of supply, "the U.S. has basic energy materials to meet its needs—at present rates of consumption—for a minimum of 200 years." However, there is a quantum jump between exploiting potential reserves and what is currently available in fuels. Bridging that gap requires time, lots of money, and the development of new technologies. And that is the primary reason why the short-term projections (up to 1985) may not be quite as rosy as the administration has indicated.

In the presentation made to the National Petrole-

The U.S. energy outlook

John G. McLean, chairman and chief executive officer of Continental Oil Company, gave his views on the energy crisis at the World Affairs Council in Pittsburgh, Pa., on September 21, 1972. Some highlights from McLean's speech, entitled "The U.S. energy outlook," follow—

Let me begin with the facts. The U.S. energy problems lie primarily in the medium-term future through the mid-1980s. From a long-term standpoint our basic energy position is reasonably sound. Our country is liberally endowed with energy materials. To meet our long-term energy requirements, we have large potential resources of crude oil, natural gas, coal, uranium and shale oil. Based on recent estimates of the National Petroleum Council, we have:

- *Potentially recoverable oil reserves sufficient to meet present demands for more than 65 years.*
- *Potentially recoverable gas reserves sufficient to meet present demands for more than 50 years.*
- *Measured and indicated coal reserves . . . equivalent to nearly 300 years' supply.*
- *Potential uranium resources sufficient to meet our present total electric power needs for 25 years.*
- *Recoverable shale oil reserves sufficient to meet our oil needs . . . . for about 35 years after our natural oil reserves are exhausted.*

Taken in aggregate, our basic potential energy resources have a [thermal] content sufficient to meet our needs for at least 200 years, at present consumption rates. Long before the end of that period, advances in technology should bring us new energy sources, such as nuclear fusion and solar power [that] will greatly diminish the drain upon our . . . energy materials. As time goes along, additional supplies of energy will be forthcoming only at significantly higher costs, but nonetheless we have the basic materials and technology to meet our long-term energy goals.

In the medium term—through about 1985—our situation is quite different because if . . . we do not act wisely and promptly, we may [have] domestic energy shortages of major proportions . . .

The critical "balance wheel" in this whole situation will be the volume of foreign oil imports, because this will be the element which will adjust for our failures or successes in other energy areas . . . Most of the oil [must] come from the 11 Organization of Petroleum Exporting Countries (OPEC) . . .

Dependence upon a small number of distant foreign countries . . . suggests that we will need to take a new look at all our foreign policies with respect to the Middle East and attach to them a much higher priority than they have thus far been accorded . . . Our domestic economy will be vitally dependent upon peace in that troubled area . . .

Our growing requirements for oil and gas imports provide a large and growing deficit in the United States' balance of trade in fuels. By the early 1980s, this deficit could be in the $20 to $30 billion range, as compared [with] a current deficit of less than $3 billion.

To pay for our imports of fuel, we will need . . . additional exports of other goods and services . . . . What will we sell and to whom? . . . The industrialized countries of Western Europe and Japan . . . will be struggling to increase their own net exports to pay for growing fuel imports. Ultimately, the situation can come to equilibrium on a worldwide basis only when the oil exporting countries are able to absorb greatly increased imports from us and the other oil importing countries.

At the present time, the composite wholesale cost of energy consumed in the U.S. is about 35 cents per million BTUs. By 1985, it could easily be 50 to 100 percent higher . . . .

um Council by McLean and Warren B. Davis, director of economics, Gulf Oil Corporation, entitled "Guide to National Petroleum Council Report on United States Energy Outlook" (released on December 11, 1972), the first paragraph is intriguing:

"The National Petroleum Council's studies reveal that U.S. requirements for energy will approximately double between now and 1985. During this period, we shall have to rely upon oil, gas, coal, and nuclear power to meet over 95 percent of our requirements. New domestic supplies of these four basic energy sources are not being developed fast enough to meet our needs."

In its summary, the report lists three options:

- The U.S. could depend upon increased overseas imports of oil and gas to meet national requirements; but this would impair national security and trigger an awesome deficit in our balance of trade in fuels.
- Through imposed restrictions, the U.S. could reduce the growth in energy consumption and demand the more efficient use of energy. But such impositions could impair the nation's life style and trigger an even more onerous deficit in its balance of trade in fuels.
- The U.S. can accelerate the development of its domestic energy resources. (This option is strongly recommended by the council.)

The thrust of the NPC's summary, however, may be found in the observation: "Fortunately, [the U.S. has] an adequate energy resource base. Action taken now would markedly improve [its] energy situation in future years. To attract the vast capital requirements to develop [its] indigenous resources, [the U.S.] will need higher prices and appropriate national energy policies."

Some NPC remedies. The council's summary concludes with a nine-point list of recommendations urging

1. Coordination of energy policies at the national level.
2. Development of realistic, graduated approaches to environmental goals.
3. Accelerated leasing of federal lands for exploration—particularly the outer continental shelf.
4. Continuation of tax incentives to encourage the finding and development of all energy supplies.
5. Maintenance of oil and uranium import controls.
6. Greater usage of electricity generated from domestic coal and uranium.
7. Relaxation of wellhead price controls so that natural gas prices may reach a competitive market level.
8. Expanded research in certain carefully selected areas (alternative methods of electrical generation, for example).
9. Reliance upon private enterprise as the best and lowest cost method of meeting energy needs.

Conservation: a positive position

A noted naturalist presents the 'case for conservation'— and some fuel/energy-use planning

As an overview, Gordon Friedlander's first article on the energy crisis (*IEEE Spectrum*, May 1973) is completely fair and helpful in developing interesting details. But like almost all discussions of the problem to date, it addresses only the supply side of the supply-demand equation. This is not surprising because the U.S. has, as a nation, assumed—more implicitly than explicitly—that our national requirements for energy are a *fait accompli* that is not subject to question. Having made that assumption, it seems patriotic to bend our energies to providing what "the nation must have." Recently, the writer heard one utility spokesman object to having his operations classified as "commercial" because, in view of New York City's hot spell last June, it should be obvious that his company was engaged in "public service."

There are obvious, often emphasized, correlations between increasing consumption of electricity and the high-consumption society we have enjoyed—especially over the last generation. Of course, we all tend to complain about the unanticipated by-products of the new life styles built on intensive mechanization and electrification: rising pollution, deteriorating cities, the disappearance of amenities in the countryside, social unrest, and alienation. All these factors are also correlated, as though they were the penalty of what we have (perhaps too long) called "progress." Some scientists and engineers still insist this *is* the price tag, but increasing numbers of people refuse to "buy it" because they have discovered that technologists are often no better analysts than laymen.

Economist Ezra Mishan is one of the new analysts and, in *The Costs of Economic Growth* (1967), he says bluntly that for "every foot of red carpet industry has unrolled before us, it has rolled up a yard behind us." For an economist of Mishan's stature to arrive at conclusions that support our intuitions and partial analyses is, of course, delightful; but each of us can make his own case.

Like the early mission of the National Audubon Society, the writer's early training and interests were ornithological—devoted to the study of birds, their interrelationships with their environment, and the problem of conserving their populations. Therefore, it often seems to many that we are erecting a hobby to serve as the framework of national policy for a majority of people who hardly know birds exist (and, frequently, couldn't care less). But it is a fortunate accident of history that those interested in bird conservation were among the first to notice—and decry—the environmental deterioration that has been the "happenstance" result of our particular brand of progress. Birds in their native habitat supply the same sort of clues to environmental health as the miner's canary did in warning of dangerous gas accumulations in the deep shafts of yesterday's underground mines (now so widely abandoned in favor of surface strip mining).

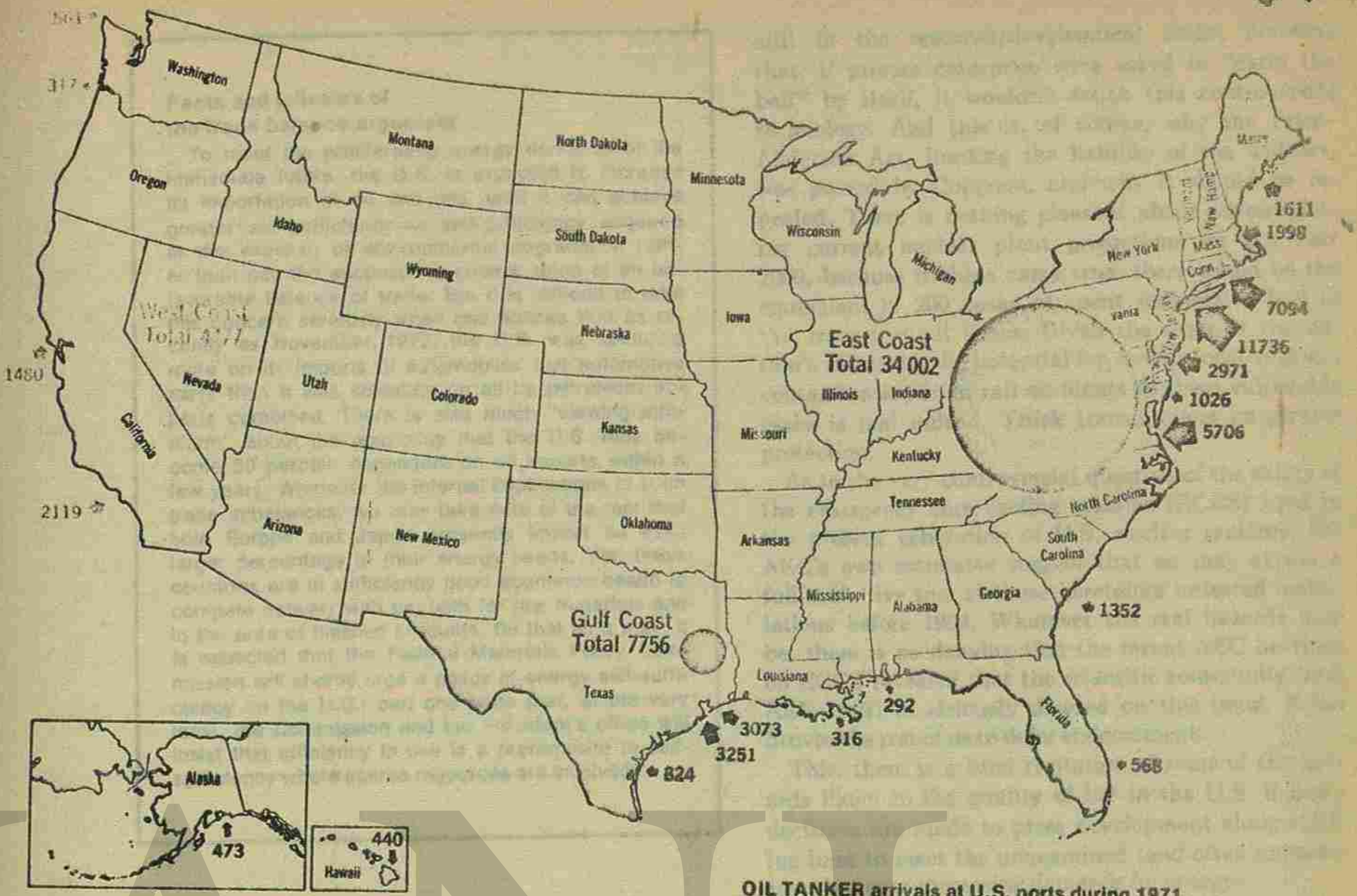
Following World War II, when new earth-moving technology facilitated drastic landscape modifications, environmentalists gradually awakened to the fact that legal protection for wildlife—and traditional public education—would not suffice to ensure coexistence with the cumulative technological advances of the first half of the 20th century. Thus, the conservation problem became one of national land-use policy—or a reaction to the lack thereof—and the conservationist-environmentalist became an activist. This meant challenging the entire "growth-progress mythology" based on the conviction that *progress* needs to be redefined. The environmental revolution of our day is an insistence, through increasing public demand, that national policy be an open planning process.

Industry spokesmen have traditionally argued that "the demand for energy is basically related to a desire on the part of everyone to improve his standard of living." The writer challenges this because he believes there is impressive evidence that the current swollen demands for energy are a result of our national policy of "cheap energy," and of the aggressive—almost irresponsible—advocacy of more and more consumption by growth-minded industrialists. This prolificacy has made the U.S. inefficient as a nation, and the public is so badly misinformed about the implications of current energy practices and policies that it does not know how to achieve its desires.

Why a crisis?

A recent Congressional review of energy-demand projections by Government agencies and industry groups, financiers, and economists revealed that almost all such projections have been merely extrapolations of post-World War II growth spurts. They are almost all useless as policy guidelines because they were based on the assumption that (1) prices would remain relatively constant, (2) fuel would remain generally available, (3) Government policy would remain relatively unchanged, and (4) there would be gradual technological improvement in energy production. All these assumptions began to prove ill-founded around 1969.

Roland C. Clement National Audubon Society



OIL TANKER arrivals at U.S. ports during 1971.

It is striking (and dismaying) that, until 1968, all studies and projections of energy "demand" in the U.S. were completely sanguine concerning the ability to continue to meet escalating growth needs. The crisis that has developed in the last five years, therefore, exposes serious failures in the planning within industry and Government agencies, and even by the Office of the President.

Shifting the blame

Energy producers have aggressively sought to shift the blame for the impending crunch we may expect from these planning failures. They have pointed an accusing finger at environmentalists' demands and at the National Environmental Protection Act of 1969. But both former AEC Commissioner Schlesinger and the chairman of the Council on Environmental Quality, Russell Train, have agreed that this is not valid.

For example, of the 75 major nuclear plant delays in effect as of May 1973, only nine of these involved environmental debate; the others were delays caused by the AEC's own early overconfidence regarding atomic reactor safety, by increasing construction-schedule slippages, and by labor difficulties.

A broader view

Granted that we may be in for some uncomfortable readjustments in our uses of energy resources, the greatest danger of the energy crunch is a series of panicky reactions by both Government and industry. This is why it is important to identify accurately the causes of present shortages, and to clarify options on the subject.

The time has come to broaden national policy to make explicit recognition of (1) the inefficiencies which result from current "cheap energy" policies; (2) the environmental damage imposed on the citizenry by past resource exploitation, and the threat of much greater environmental damage if hasty decisions to continue present modes of demand satisfaction are implemented; and (3) the new danger of aggravated international divisiveness if our current "demands" are made the basis of confrontations with petroleum suppliers abroad.

Consider these environmental hazards. In 1971 there were 46 235 tanker arrivals at U.S. ports (see illustration; source: *Waterborne Commerce of the United States*, Department of the Army, Corps of Engineers), and, on an average, these moved 4.5 million barrels of oil per day. The usual projections suggest that by the year 2000, our imports could be 25 million barrels per day. Already some 2 million tons of these hydrocarbons enter the ocean each year, only 10 percent of them, however, from tanker oil-spill accidents. The balance comes from careless or irresponsible handling on shore and at sea. Many authorities are already greatly concerned that the productivity of the oceans will be destroyed by such levels of pollution.

Current projections also call for the importation of

Facts and fallacies of the trade balance argument

To meet the proliferating energy demands of the immediate future, the U.S. is expected to increase its importation of oil and gas, until it can achieve greater self-sufficiency—a self-sufficiency acquired at the expense of environmental degradation rather than pay the supposed economic price of an unfavorable balance of trade. But it is difficult to take this concern seriously when one notices that as recently as November 1972, the U.S. was spending more on its imports of automobiles and automotive parts than it was spending on all its petroleum imports combined. There is also much "viewing-with-alarm" about the possibility that the U.S. may become 50 percent dependent on oil imports within a few years. Whatever the internal implications of such trade imbalances, we may take note of the fact that both Europe and Japan presently import an even larger percentage of their energy needs. Yet, these countries are in sufficiently good economic health to compete actively with us, both for raw materials and in the area of finished products. Be that as it may, it is expected that the Federal Materials Policy Commission will shortly urge a policy of energy self-sufficiency on the U.S.; can one hope that, at the very least, the Commission and the President's office will insist that efficiency in use is a prerequisite to self-sufficiency where scarce resources are involved?

2 to 4 trillion ft³ of liquid natural gas (LNG) by 1990, which would involve a fleet of some 200 specially-equipped supertankers. Since LNG is stored and transported at a temperature of 147K, a major accident would probably cause the tanker's load to vaporize within half an hour, forming a cloud of combustible gas a mile in diameter, and perhaps suffocating all those under it. If ignited, as would seem inevitable, an explosive conflagration of mammoth proportions would follow. The hazard to port cities is obvious.

Many hapless citizens who live in mining towns or near oil fields are aware that 2 million acres of the U.S. have already subsided a few meters. Others are well acquainted with the wastelands created by the 1.5 million acres that have already been strip-mined, and the 64 000 acres being stripped annually. Since nearly half of our remaining coal is now located in Montana, Wyoming, and North Dakota, the proposals to strip this region pose monumental problems of reclamation. And since this region is mostly semiarid, expensive interregional water transfers will be a necessary added cost of mining or stripping this coal. The oil shales of the Colorado Plateau will also be difficult to exploit without water transfers, and the land reclamation problems in that rugged region are even more difficult. Not many people use the high plains, but Colorado is one of the major recreational areas of the U.S., and the tradeoffs involved here have hardly been discussed.

The enthusiasts for nuclear energy need to be reminded that all current proposals for the long-term storage or other disposal of nuclear plant wastes are still in the research/development stage, meaning that, if private enterprise were asked to "carry the ball" by itself, it wouldn't touch this controversial technology. And this is, of course, why the Price-Anderson Act, limiting the liability of the utilities, was passed by Congress, and why it should be repealed. There is nothing pleasant about contemplating current nuclear plant projections for the year 2000, because if these came true, there would be the equivalent of 200 casks of spent radioactive fuel in rail transit at all times. Given the state of the nation's railroads, the potential for serious local-regional contamination from rail accidents to these vulnerable casks is real indeed. Truck transit offers no greater protection.

As to the very controversial question of the safety of the emergency core cooling systems (ECCS) used in the present generation of U.S. nuclear reactors, the AEC's own estimates suggest that we may expect a full-scale live test of these heretofore untested installations before 1983. Whatever the real hazards may be, there is no denying that the recent AEC hearings on ECCS revealed that the scientific community (and AEC staff) is seriously divided on this issue. It behooves the rest of us to defer endorsement.

This, then, is a brief recitation of some of the hazards likely to the quality of life in the U.S. if hasty decisions are made to press development along existing lines to meet the unexamined (and often unnecessary) but ever-increasing demands for energy.

A revolution in outlook

One of the overlooked but very significant indicators of the public temper resulting from the spreading affluence of the last generation is a new insistence on the preservation of natural amenities. This has always been obvious to those who have taken the trouble to notice that Wall Street's tycoons, and a whole generation of Madison Avenue's successful promoters, commute to suburban towns like Greenwich, White Plains, and Darien, where they can enjoy clean air, greenery, or an attractive waterfront. Now, we know this to be a general characteristic of large segments of our population. Wilderness visitation, for example, which has grown at the rate of 10 percent per year since World War II (faster than the consumption of electricity), is engaged in mostly by affluent, well-educated, urban professionals.

The new "conservation economics" pioneered in the U.S. by John Krutilla of Resources for the Future, Inc., and a growing number of colleagues, has demonstrated that the demand (value) for natural amenities is growing rapidly, both as these amenities grow scarcer and as incomes increase. At the same time, it is becoming necessary to discount the future worth of many technologies simply because technological progress creates so much obsolescence in its own field. Therefore, those who believe in technological progress should be among the most patient of men because tomorrow's technology should allow us to do *what really needs doing* both better and more cheaply.

These introductory comments on affluence have surely reminded most readers that today's "big pitch" by the utilities and other energy producers is that

Nuclear waste hazards

Recent disturbing news reports have indicated that a serious (if not calamitous) problem may be arising in the leakage of nuclear plant wastes—through the disintegration of the cask and containers—at the large tank farms located at Hanford, Wash., the Idaho Chemical Reprocessing Plant, and the Savannah River Plant. (In fact, one report states that waste leakage has been percolating through to the ground surface.)

In Marce Eleccion's piece "Scanning the Issues" (*IEEE Spectrum*, April 1970), he quoted W. de Laguna, of the Oak Ridge National Laboratory, in part as follows:

". . . the problem of coping with these highly hazardous liquid wastes has been with us for about 25 years. Until very recently, all that could be done with these wastes was to put them into large tanks, and large tank farms, holding in all some *80 million gallons* of high-level waste, have grown up over the years . . . If the contents of even *one* of these tanks should reach the river which drains one of these areas, *there would be a regional calamity of unprecedented magnitude;* and there are now over a *hundred* such tanks at these three installations. Although these tanks are constructed with great care, there have been a number of tank leaks . . . ."

It should be noted that this piece was published almost 3½ years ago. Since that time, of course, additional wastes have accumulated. And, with the advent of the fast breeder reactor (FBR), the situation —in which plutonium wastes must be handled— makes the prospects for the future even more acute. Plutonium, the most dangerous of the radioactive elements (used in nuclear weapons), has a half-life of 200 000 years.

In addition to the problem of waste storage, there is the hazard—and a very real one—of theft of these deadly materials. It is a subject of ongoing concern. Thus, the future holds some very serious questions that must be resolved in these areas.

—Editor

growth must continue, if only to bring the nation's poor into the sphere of affluence the rest of us enjoy. But this is only a modern version of the old "trickle down" theory of economic welfare. It hasn't worked during the last century or more that we have preached it, and it won't work tomorrow. The poor are often caught in an ecological trap created by the unconcern of the affluent who pollute the landscape. Pollution is dehumanizing to all those who suffer from it, and the poor have suffered from it most. If we want to eliminate poverty, we will have to do it by more direct means.

Policy needs

Environmentalists insist, rationally this writer thinks, that the cornerstone of our national energy policy should be one of energy conservation. Achieving this goal will require:

1. The imposition of the full economic and social costs of energy on the consumers of energy, and the imposition of adequate environmental safeguards on the producers and distributors of this energy. (Only thus can we restore the selective function which true market prices are supposed to exercise in a capitalistic system; this will allow the consumer to decide which goods he values most.)

2. The elimination of economic subsidies to energy industries for doing what small business does without subsidy in response to public demand for goods at a fair price.

3. The imposition of performance standards on the building industry and the manufacturers of energy-consuming equipment to eliminate the wasteful "built-in obsolescence" characteristic of so much production in the U.S. today, along with the multiplicity of inefficiencies this system has bred. (We must aim at "life-cycle" assessments that will show the consumer what the real costs of buying *and operating* a home or an appliance will be.)

4. A shift in transportation policies from inefficient huge automobiles and intercity trucks and aircraft to more energy-efficient railroads, buses, etc. (Much of this will come about automatically as soon as we impose the full social costs of energy and eliminate subsidies that now favor inefficient transportation.)

The objective of conservation policy is to make our society more efficient by removing distortions of the market system inherent in subsidies. Low-income consumers who might otherwise be hurt by these regressive changes in the cost of basic commodities must be helped by higher minimum wages, negative income tax, or other appropriate institutional arrangements. As already hinted, however, the poor may suffer more from pollution and built-in obsolescence than from other economic disadvantages. Eliminating the declining rate structures for large consumers of electricity will hurt many public-service groups such as school systems, hospitals, etc., but we will end up better off by making our taxes direct instead of resorting to the smokescreen of indirect taxation that now makes us so inefficient. Energy conservation has the potential for saving between 20 percent and 50 percent of our existing consumption levels. Like it or not, we must conserve to avoid more severe constraints.

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Energy

Plumbing the ocean depths: a new source of power

Temperature differences between surface and deep waters of tropical oceans can provide cheap power

Faced with a shortage of fossil fuels, rising costs of nuclear fission power plants, and long delays in introduction of nuclear fusion power plants, researchers in the U.S. are looking with renewed interest and a sense of urgency at nontraditional—and, in most cases, unproved—alternate energy sources such as tidal energy, geothermal energy, and solar energy In the solar energy field, for example, there are on-going investigative programs in satellite solar power stations, solar energy for buildings, solar thermal conversion, conversion of organic materials, photosynthetic production, wind power, and solar sea power—the technology that will be addressed herein.

The main difficulty in harnessing solar energy is collecting it. Land-based collection mechanisms require huge land areas and expensive materials for the direct or indirect conversion of solar energy into electricity or other forms of energy. But, in the case of solar sea power, the collection mechanism is the ocean. Solar energy, absorbed by the surface water of tropical oceans, can be converted first into electric power by solar sea power plants (SSPPs), then converted by electrolysis into chemical energy, and transported by ship to the U.S. for distribution to heat homes, power transportation facilities, and form a basic ingredient in materials processing.

The concept of solar sea power is not new. In 1881, D'Arsonval pointed out the possibility of extracting energy from the tropical oceans by building a thermal engine operating on the temperature differences between surface water and deep layers of water.[1] And, in 1930, the French engineer Georges Claude actually attempted to build a 40-kW power plant off Cuba,[2] but his experiment failed for a number of technical reasons. More recently, Anderson and Anderson made detailed cost studies of such a sea thermal power plant[3] and estimated that a 100-MW plant could be constructed at a capital cost per kilowatt no higher than that for a conventional fossil-fuel plant.

The scientific basis for an SSPP has not been questioned. But for engineers accustomed to thinking in terms of temperature differences of a few hundred degrees and super-heated steam, the available temperature differences for an SSPP seem miniscule. And other questions have been raised: corrosiveness of sea water, microbial fouling, plant anchoring, diluteness of solar energy in the ocean, and environmental effects. Each question will be examined in turn.

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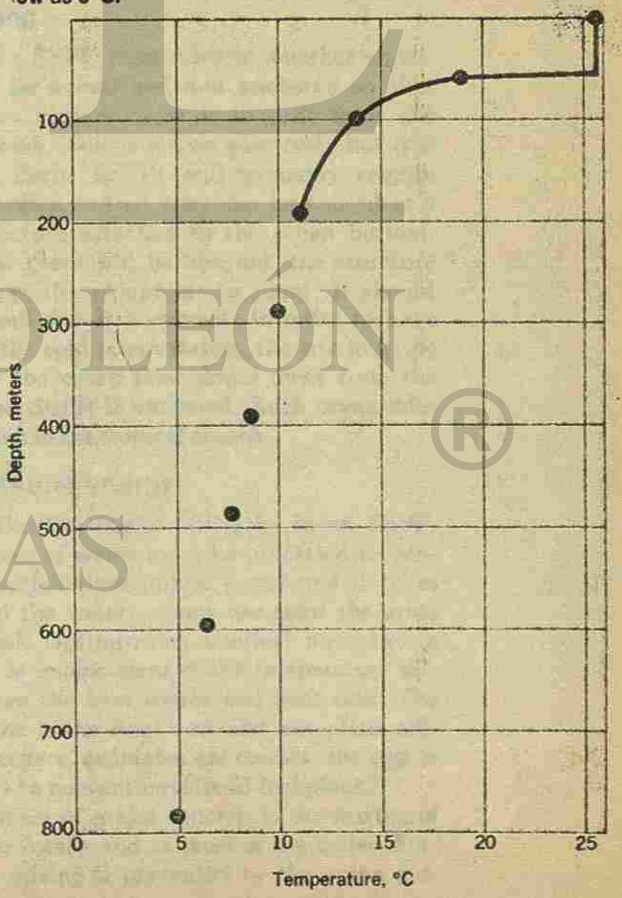
Insufficient temperature difference

Conventional fossil-fuel power plants operate with a temperature differential of 500°C between the heat source and the heat sink. In the ocean, there is at best a 20°C temperature differential between the warm surface water and the readily accessible deep cold water, as shown in Fig. 1. And of this 20°C, only 10°C can be used by the heat engine itself. The remaining difference is needed to drive heat from the warm surface water into the heat engine and then from the heat engine to the cold deep water. (A design concept for an SSPP operating on such a temperature differential is shown in the box on page 25.)

[1] Typical ocean temperature profile at various depths. The surface layer, which is about 200 meters deep, takes its heat from the sun and stays at about 25°C. The cold water at the lower depths comes from the Arctic region and can be as low as 5°C.



In an SSPP, a working fluid such as ammonia—or any fluid with a reasonably high vapor pressure at ambient temperature and with good heat transfer characteristics—must be boiled. Normally, to promote vigorous boiling, the working fluid must be superheated by from 5-10°C. But in an SSPP with only a small total temperature differential available, a 3°C superheat is the highest that can be afforded. One solution to the problem of a small superheat may lie in a technique that was used by the Linde Corporation in their refrigeration systems[4] where they encountered a similar problem. The solution came about through development of a method for cutting tiny, almost closed, channels on the surface of a metal. The channels become vapor-locked and, thereby, provide a steady stream of bubbles. Such a surface needs a superheat for boiling only one-tenth that of conventionally smooth surfaces.

Even with the boiling problem solved, the 20°C temperature differential might seem to create a cost handicap because it leads to a low efficiency—3 percent—compared to nearly 40 percent in a conventional plant. For a given kilowatt output, the SSPP boiler must process more than ten times as much heat as the boiler in a conventional plant. In particular, the SSPP boiler tube area must be more than ten times greater than that in a conventional plant. Although this requirement would seem to necessitate excessive cost, two basic physical phenomena enter the picture that tend to offset any cost increase and may even permit a cost decrease.

The first phenomenon is that the vapor pressure of a working medium rises rapidly as its temperature increases. This pressure increase must be offset by a corresponding increase in thickness of the boiler tubes. Since in an SSPP the maximum pressure anticipated is only about 150 psi (about one million N/m^2), compared to 3200 psi (about 22 million N/m^2) in conventional steam boilers, much thinner boiler tubes can be used.

The second phenomenon is the decrease in strength of metals with a rise in temperature that, in a conventional boiler, must be offset by an increased wall thickness or by the use of expensive alloys. Again, an SSPP benefits because the temperatures in use are small compared to those in conventional plants.

The increase in cost of boiler tubes because of either of these phenomena—or both—in conventional plants can be nearly catastrophic. For example, in the mid 1950s, the Eddystone power station was constructed in Philadelphia with a boost in peak temperature to 600°C. The drastically increased cost of the station required by the higher temperature was the death blow for plants above 500°C.

Corrosiveness of sea water

Because of the electric conductivity of sea water, metallic structures submerged in the ocean suffer electrolytic corrosion. A quantitative measure of the tendency of a metal to dissolve in water is its electrochemical potential. Those metals with a positive potential will dissolve spontaneously with the evolution of hydrogen. Those with a negative potential will not dissolve. Inexpensive metals such as iron have positive potentials while only expensive metals such as copper, silver, and gold have negative potentials.

Pure aluminum has the unique characteristic of forming a tightly clinging oxide coating which protects the metal from contact with water. Thus, in spite of its positive electrochemical potential, pure aluminum will not dissolve in sea water. The Aluminum Company of America has learned how to take advantage of this oxide coating on pure aluminum by bonding a layer of pure aluminum onto a high-strength aluminum alloy. Such a bonded structure is called Alclad. During the last several years, test data have been accumulated[5] demonstrating that Alclad tubing would have a long service life in SSPPs. It should be noted that life tests were conducted at elevated temperatures of up to 80°C where corrosive effects are much more severe than at the ambient temperature of an SSPP.

Microbial fouling

All surfaces submerged in sea water soon become covered by a film of microbes, a film that would ruin the heat transfer characteristics of boiler surfaces. The Woods Hole Oceanographic Institute has found, however, that an exceedingly small concentration of chlorine—less than one part in four million—is sufficient to prevent such microbial growth[6] and is far below that required to kill marine life.

When chlorine gas is added to sea water, it forms hypochlorous acid which can also be formed directly by electrolysis of sea water. The electric power required for the electrolysis is a small fraction of that generated by an SSPP. This electrolysis could take place in the input pipes of an SSPP. In fact, such electrolytic equipment has already been developed for use in the intake condenser pipes for power plants located on sea coasts.

Plant anchoring

To protect an SSPP from adverse weather conditions, it must be submerged and anchored so that oceanic currents cannot cause it to drift from one location to another. This is not an easy task, but it is surmountable. Early SSPPs will probably require careful site selection so that they can be housed in a permanent structure attached to the ocean bottom. Since the power plant will be buoyant, the structure need not support the weight of the plant. It should merely withstand the drift current. In order to have easy access to the cold ocean waters, the site must be selected where the ocean floor slopes away from the point where the SSPP is anchored. Such ocean-floor cliffs are common in the tropical oceans.

Diluteness of solar energy

Because of the low engine efficiency in an SSPP, immense volumes of water must be processed to generate any appreciable amount of power and it takes power to pump the water—about one-third the gross power generated. Optimization studies[7] have shown that this ratio is independent of the temperature differential between the heat source and heat sink. The important factor is the final cost and not plant efficiency. If the writers' estimates are correct, the cost is still below that of a conventional fossil-fuel plant.

Another problem of major concern is the mixing of the warm water intake and exhaust of the boiler. Fortunately, such mixing is prevented by the ocean currents. Currents of 0.5 meter/second would prevent appreciable mixing in a 200 000-kW SSPP.

Environmental effects

Solar energy is probably the only pollution-free source of energy. Although its widespread use could lower the surface temperature of the tropical oceans, a tremendous amount of energy would have to be extracted in order to cause a noticeable effect. For example, if the world population in the year 2000 were to be supplied by energy from SSPPs at the present per capita rate of consumption in the U.S., the surface temperature of the tropical oceans would be lowered by less than one degree Celsius.

Markets for SSPPs

The first market for SSPPs would probably be the local use of electric power in those countries bordering on tropical waters. Although such a market would be small, it would provide the necessary operating experience required for large-scale planning. Table I lists those countries whose coastal waters have the year-round thermal characteristics required by SSPPs and gives the distance, in kilometers, from land to an ocean depth where the water is sufficiently cold (5°C) to be suitable as a heat sink. It is noteworthy that the tropical waters closest to the U.S.—the Caribbean—are unique in having cold deep water within two kilometers of the coast of most of the bordering countries.

The second market for SSPPs would probably be for a power-intensive metallurgical industry which always develops wherever there is cheap electric power. The production of aluminum is a good example.

More than one half the bauxite reserves in the Americas are in Jamaica.[8] Bauxite is mined in Jamaica by all the large U.S. aluminum-producing companies. They ship the ore to the Gulf Coast and there refine it into alumina (aluminum oxide). The alumina is then shipped to all parts of the U.S. where electric power is cheap. Some is even shipped back into the Caribbean, through the Panama Canal, and then up the West Coast of the U.S. to cheap hydroelectric power in the state of Washington. Since Jamaica could enjoy an abundance of cheap electric power generated by SSPPs, a more economical process would be the refining of bauxite into alumina and the electrolytic reduction of alumina into metallic aluminum on the island itself. (For a detailed analysis of costs in producing aluminum, see the editorial box on page 26.)

Other large reserves of bauxite are also located in countries bordering tropical oceans—Ghana in Africa, Surinam and the Guianas in South America, and Australia. As shown in Table I, these countries are all located a considerable distance from the deep cold water required as a heat sink. This situation might lead to a third stage in the marketing of electric power from SSPPs with the development of floating metallurgical complexes, as described by Willy Ley.[9]

The third market for SSPPs is energy for use in the continental U.S. and in other locations in the temperate zone—Europe, U.S.S.R., and Japan. Since favorable sites for SSPPs are confined to the tropical oceans, how can generated power from SSPPs be used by these countries? A proposed method of transport-

I. Minimum distance from coast to suitable SSPP location for countries that border warm tropical waters

	Distance, km
Countries bordering Indian Ocean (clockwise order):	
Madagascar	32
Mozambique	25
Tanzania	25
Kenya	25
Somali Republic	25
Southern Yemen	32
Muscat and Oman	6
Iran	32
Pakistan	32
India:	
West Coast	120
East Coast	65
Burma	75
Countries bordering Pacific Ocean (clockwise order):	
Hawaii	10
Mexico	25
Guatemala	32
El Salvador	65
Honduras	75
Nicaragua	95
Costa Rica	7
Panama	25
Columbia	25
Ecuador	25
Australia:	
Northeast corner	65
Otherwise	300
New Guinea	5
Java	5
Philippines	5
Vietnam	75
Sumatra	50
Countries bordering Atlantic Ocean (clockwise order):	
Sierra Leone	50
Liberia	50
Côte d'Ivory	50
Ghana	50
Dahomey	50
Cameroun	65
Brazil:	
1° to 20° South	15
Otherwise	100
French Guiana	130
Surinam	130
English Guiana	130
Venezula	3
Columbia	32
Panama	25
Costa Rica	15
Nicaragua	150
Honduras	24
Mexico	7
United States of America:	
Florida	1
Puerto Rico	6
Cuba	2
Jamaica	2
Haiti	2
Dominican Republic	2
Guadeloupe (French)	2
Dominica (British[2])	5
Martinique (French)	2
St. Lucia (British[1])	2
St. Vincent (British[1])	2
Grenada (British[2])	2

[1] Distance to 5°C water at 500 meters.

[2] Freely associated with Britain.

ing energy from SSPPs is tied in with the so-called hydrogen economy.

The hydrogen economy

While electric power can be useful in many ways, an all-electric economy is not feasible for several reasons. First, the cost of transmission is too high. On a BTU or kWh basis, it costs more to transmit electric energy over a long distance than to ship fuel through a pipeline. Second, electric energy cannot be stored as efficiently as fuel. Third, there are many applications—notably, transportation and industrial processes—where fuel is irreplaceable. These observations have led to the concept of the hydrogen economy.[10]

The basic idea in a hydrogen economy is to generate electricity by ringing the U.S. shores with floating nuclear power plants. Since a large percentage of the U.S. population is located within 150 kilometers of water fronts, all electric energy needs could then be

How a solar sea plant works and what it costs

The basic components of a solar sea power plant are shown in the accompanying illustration. Operation of the plant is as follows:

Warm water is pumped into the boiler to boil the working fluid—a fluid that boils at ambient temperature under moderately high pressure. Ammonia is indicated in the illustration as the working fluid. It meets most of the requirements for a low-temperature-difference cycle. But ammonia does present other problems that might preclude its use in favor of freon, propane, or a number of other substances.

The ammonia gas under "high pressure" is fed into a turbine–generator and is discharged at "low pressure" into the condenser, which also receives cold water from the deep ocean. Ammonia liquid at low pressure from the condenser is then pressurized and pumped to the boiler. The cycle is then repeated.

The total temperature difference between warm and cold water is about 20°C. It must be allocated optimally among the boiler, the turbine–generator, and the condenser. In the boiler, heat must flow from the water to the boiler tubes and then to the working fluid. A similar heat flow takes place in the condenser.

The manner in which the available 20°C is divided among the boiler, turbine–generator, and condenser influences the overall cost of a power plant. If, for example, 10°C is allocated to the heat exchangers in the boiler and in the condenser, the Carnot efficiency is only 3.3 percent. With such low efficiency, the boiler and condenser must process enormous volumes of water. If conventional heat-exchange technology had to be used, the cost would be prohibitive. By being able to install the boiler and condenser underwater at convenient depths where water pressure on the outside can equalize internal pressures, construction can be relatively "flimsy" with thin tubes throughout. This construction has the double advantage of enhancing heat conduction on the one hand and drastically reducing cost on the other. Anderson and Anderson[3] have proposed such an installation where the boiler is placed below the condenser by a few hundred feet so as to equalize the pressure on each unit. In a practical design, one must weigh the economy versus the resultant increase in water pumping and overall system complexities.

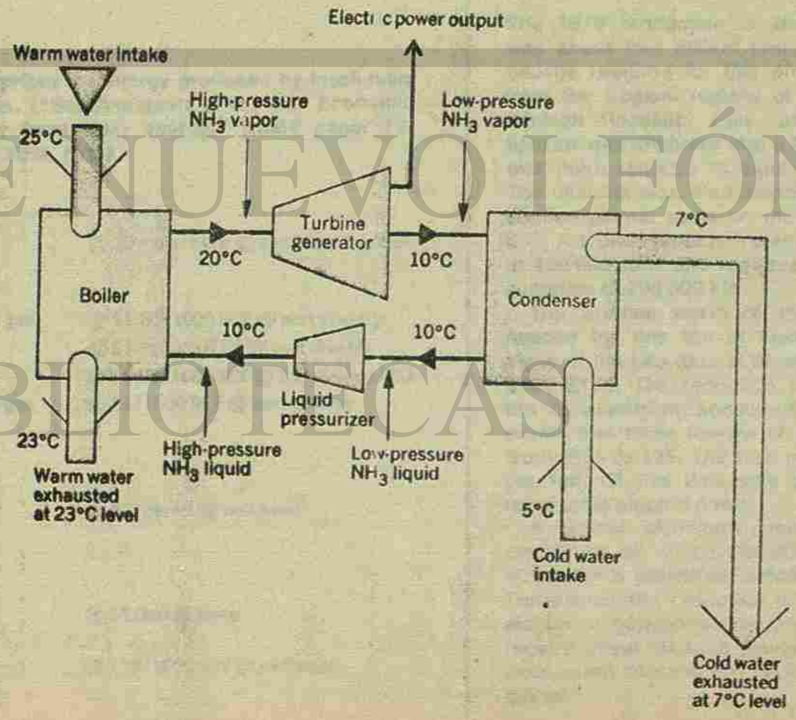
With specially prepared heat transfer surfaces—controlled roughness on the water side, vapor traps on the boiling surface, and vertical corrugation on the condensing surface—heat transfer coefficients as high as 2000 BTU/h·ft²·°F or 12 kW/m²·°C may be obtained. With this technique, boiler plus condenser costs should not exceed $30 per kilowatt.

A complete breakdown of power-plant costs beyond the early experimental units has been detailed by Anderson. The accompanying table compares the generation costs of SSPP with conventional and nuclear power plants.

Generation cost comparison

Energy Source	Capital ($/kW)	Fuel (mills/ kWh)	Total (mills/ kWh)
SSPP*	165	0	3
Fossil fuel	300–360	4	10–11
Nuclear	500**	2	12**
Breeder	500	1	11

*These figures appear optimistic and require close reexamination.
**Latest figures according to NUS Corp. See *The New York Times*, Nov. 26, 1972, p. 1.

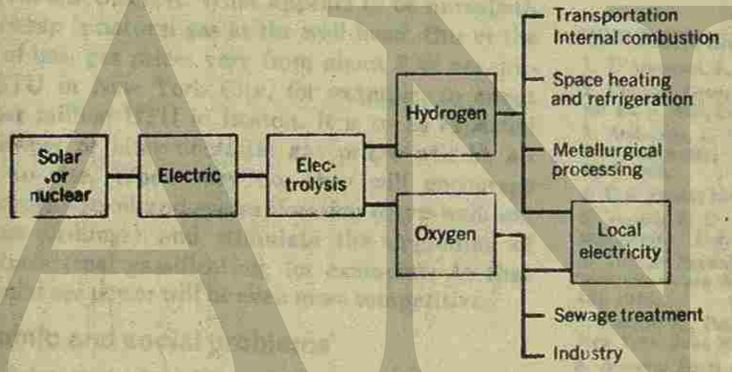


met directly. Furthermore, by using electric current to electrolyze desalinated sea water, hydrogen could be produced and shipped or piped inland for various uses. (It might be necessary to produce and ship liquid ammonia which would then be separated into hydrogen and nitrogen before use as a fuel.)

If a hydrogen economy is indeed desirable and economically feasible, then why not use solar energy to produce the hydrogen? Figure 2 illustrates how it could be done. It is estimated that the cost of producing hydrogen by solar sea power would be $1.28 per million BTU.

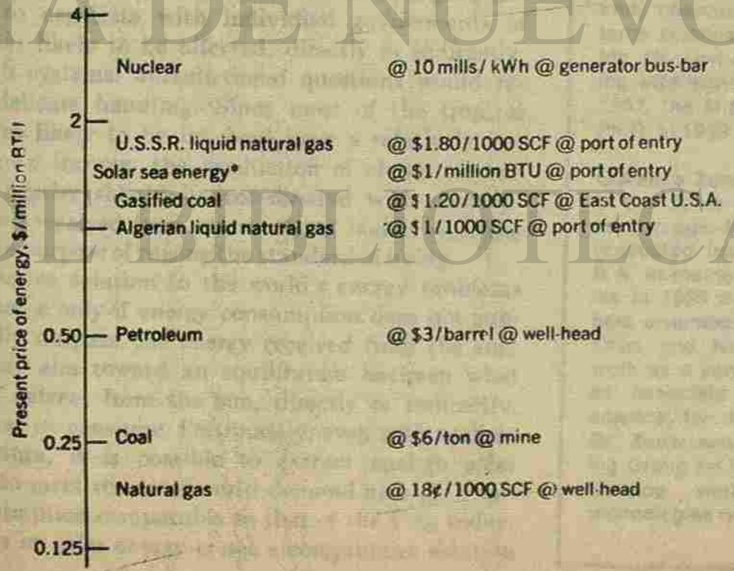
Hydrogen may be the most desirable form of fuel for electric power generation, residential and commercial heating, industry, and transportation—the four main uses for fuel.

In electric power generation within metropolitan areas, the use of hydrogen and oxygen in place of fossil fuels could reduce the cost of electric power by at least 50 percent. If hydrogen and oxygen are already pressurized, it is more efficient and economical to use an open-cycle process rather than a closed one. By burning pressurized hydrogen and oxygen in a combustion chamber rather than in a boiler, high-pressure superheated steam is generated and fed directly into the turbine. This technique eliminates one half the capital cost of a power station and results in no chemical pollutants. Therefore, power stations could be located in the vicinity of residential and commercial loads with the result that most of the power transmission costs would be eliminated. Another advantage of locating the power plants within a city would be that the rejected heat, in the form of exhaust superheated steam, could be distributed to heat residential and commercial buildings. Heating of these buildings using natural gas, petroleum, and coal constitutes 18 percent of the total fuel consumption in the U.S.



[2] Basic elements of a hydrogen economy system.

[3] Comparative prices for energy produced by fossil fuels and other sources. (*See Anderson, J. H., Jr., "Economic power and water from solar energy," ASME paper 72-WA/SOL-2, New York, N.Y.)



The fact that hydrogen burns cleanly, and reacts completely with oxygen to produce water, makes it a more desirable fuel than fossil fuels for most industrial processes. One example is the direct reduction of iron ores by hydrogen rather than by coal in a blast furnace.

Hydrogen also has many attractive features as a fuel for internal combustion engines for transportation. Its light weight compared to kerosene or other aircraft fuels would enable aircraft to have from two to three times their present range. And the absence of pollution when hydrogen is burned would provide an answer to the problem of eliminating automobile pollution.

What about comparative costs?

It is interesting to compare costs of the various common energy sources with that of solar sea power as is done in Fig. 3. Costs vary from $.18 per million BTU for natural gas at the well-head to $3 per million BTU for nuclear energy at the generator bus bar.

Electric power and the production of aluminum

The 1970 production of aluminum within the U.S. was about four million tons. The 16 million tons of bauxite required for this production came primarily from the tropical regions of Jamaica, Surinam, Dominican Republic, Haiti, and British Guiana. The bauxite was imported into a few Gulf Coast ports and was there reduced to eight million tons of alumina. The alumina was then shipped to 30 electrolytic reduction plants, some on the Northwest coast of the U.S. A typical reduction plant has an annual capacity of 100 000 tons and requires an electric power consumption of 200 000 kW.

The at-mine worth of the four tons of bauxite needed for one ton of aluminum is $20–$30. The value of the two tons of alumina derived therefrom is $100–$130. The reduction of this alumina into one ton of aluminum consumes $90 worth of electric power and three fourths of one ton of pure carbon worth $35 to $95. The final ingot sells for about $520 per ton. Of this final sale price, about 17 percent represents electric power.

A typical aluminum electrolytic reduction plant would use all of the 200 000-kW anticipated power output for a projected typical solar sea power plant. The electrolytic reduction of the four million tons of aluminum now consumed annually in the U.S. would require about 40 such plants. In order to supply the anticipated demand for 1970, 80 plants would be required.

A perspective on solar sea power

With the many alternatives to conventional power sources under consideration, it is interesting to attempt to find where solar sea power fits into the scheme of things. One strong clue is the National Science Foundation. It is active in a number of energy programs and has more than one half of its total energy funds devoted to terrestrial solar energy programs during FY1973 and FY1974.

Five-year goals and plans have been formulated by NSF for each of the following application areas: solar energy for buildings, solar thermal conversion, photovoltaic conversion, conversion of organic materials, photosynthetic production, wind energy conversion, and ocean thermal difference conversion. In FY 1973 wind energy conversion and ocean thermal conversion research received about $200 000 each out of a total budget of $3.8 million. The budget estimate for FY 1974 funding is $600 000 for ocean thermal energy conversion out of a total solar energy budget estimate of $12.2 million.

The five-year goal for solar sea power is component and subsystem proof-of-concept experiments under simulated or actual sea conditions. There will be systems studies and optimizations to identify the most economical systems. A system definition and component and system preliminary design project on ocean temperature differences is presently sponsored by NSF/RANN at the University of Massachusetts. This project also includes cooperation of the firm of J. Hilbert Anderson and the United Aircraft Research Laboratories. Another project has been initiated at Carnegie-Mellon University to develop computer based analytic models for technical and economic analyses of components and subsystems of the most important approaches to solar sea power systems.

At a conference on solar sea power at Carnegie-Mellon University in late June of this year, sponsored by NSF and organized by Professor Lavi, several technical sessions and workshop sessions were held. The workshop on power-plant siting recommended that either the Island of Hawaii or St. Croix in the Caribbean be used as the site for a small prototype solar sea power plant (1 to 10 MW) to prove the concept. The next move is up to NSF.—

R. K. Jurgen

Based on these estimates, solar sea power appears to be competitive with liquefied natural gas from Algeria and from the U.S.S.R. What appears to be unrealistically cheap is natural gas at the well-head. But at the point of use, gas prices vary from about $.42 per million BTU in New York City, for example, to about $.70 per million BTU in Boston. It is to be expected that sooner or later domestic gas prices will be allowed to rise. When they do, they will encourage more expensive oil and gas exploration (deep-well and off-shore drillings) and stimulate the upgrading of fossil fuels (coal gassification, for example). At that time, solar sea power will be even more competitive.

Economic and social problems

The nontechnical problems in implementing a solar sea power system—ranging from financing to international relations—deserve even a higher priority than design, testing, and manufacturing.

It seems desirable to have a Government organization sponsor the development of solar sea power systems. Government-backed financing might also be needed. Such an organization would be in a good position to negotiate with individual governments of countries likely to be affected, directly or indirectly, by such systems. Jurisdictional questions would require delicate handling. Since most of the tropical countries likely to be involved have a relatively low per capita income, the production of cheap electric power nearby should be coordinated with development aid received from international bodies with the ultimate purpose of raising the standard of living.

A feasible solution to the world's energy problems will emerge only if energy consumption does not substantially outpace the energy received from the sun. We must aim toward an equilibrium between what we can extract from the sun, directly or indirectly, and what we consume. Fortunately, even with such an equilibrium, it is possible to extract enough solar energy to meet the total world demand at a per capita consumption comparable to that of the U.S. today. Reliance on solar energy is not a compromise solution but a sound objective to be pursued in earnest. It deserves far more attention that it has thus far received.

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Abrahim Lavi has been a member of the faculty of Carnegie-Mellon University since 1959. He is presently chairman of a university-wide program on systems sciences and professor of electrical engineering. Dr. Lavi received the B.S. in electrical engineering with highest distinction from Purdue University in 1957, the M.S. in 1958 from that university, and the Ph.D. in 1959 from Carnegie Institute of Technology.

Clarence Zener, perhaps best known as the inventor of the Zener diode, has been a university professor at Carnegie-Mellon University since 1968. He was graduated from Stanford University in 1926 with a B.A. in mathematics and received his Ph.D. in physics in 1929 from Harvard University. Dr. Zener has held a number of faculty positions at various universities and his nonacademic career has included work as a senior physicist at Watertown Arsenal and as associate director, director, and director of science for Westinghouse Research Laboratories. Dr. Zener was appointed recently to the U.S. Working Group on Solar Energy which has been set up to develop working relationships in solar-energy technologies with the U.S.S.R.

SOLAR ENERGY PROGRESS-

Solar energy technology has made great strides in the past decade: Long-range space-craft are using increasingly large arrays of solar batteries; new solar still designs are moving in the direction of lightweight packaged units; in places like Australia, solar water heaters are on the increase; research continues in the area of solar air-conditioning both here and abroad; and, since larger and larger power sources are becoming necessary for the space program, interest is again turning to large solar concentrators.

JOHN I. YELLOTT

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THERE are two fundamental values on which most solar radiation calculations are based: (1) the average earth-sun distance, known as the "astronomical unit," and (2) the "solar constant," which is the unit intensity of solar radiation on a surface normal to the sun's rays, outside the earth's atmosphere, at the mean earth-sun distance. The most recent determination of the astronomical unit, made by J. H. Lieske of the Yale University Observatory, gave a value of 92,957,200 ± 50 miles [1].[1] Previously quoted values were 92.6×10^6 miles [2] and 92,976,200 ± 250 miles [3]; the Encyclopaedia Brittanica gives 93×10^6 miles. The differences are small but by no means insignificant in space work.

The latest and probably the most accurate determinations of the solar constant were made during 1966 and 1967 by a series of pyrheliometer measurements from aircraft flying nearly 10 miles above the earth. As reported by Drummond and Hickey [4], the most probable value of the solar constant is 136.1 mw/sq cm, which is equivalent to 1.946 langleys per min or 430.5 *Btu*.[2] The value which has been in wide use during the past several decades had been 442 *Btu* (2.00 ly/min or 140.3 mw/sq cm) derived by Johnson [5] from a compilation of data taken from a number of sources, including rocket-borne spectrographs which reached elevations of 38 miles. The Eppley-JPL value agrees closely with Dr. Abbot's best Smithsonian estimate [6], 1.940 ly/min or 429.3 *Btu*, and it is likely to remain unchallenged until an astronaut standing on the moon has an opportunity to make an unhurried measurement with a high-precision solar radiometer.

The spectral distribution of the sun's radiant energy in outer space is as important to satellite designers as is the exact value of the solar constant. Until that moon-based astronaut has an opportunity to make direct spectrographic measurements, the curve derived by Johnson in 1954 [5] stands as the most reliable estimate of the solar spectrum. On the surface of the earth the curves devised by Parry Moon in 1940 [7] have been the engineering standard. Moon based his work on the Smithsonian solar constant, and it now seems that he was very close to the best attainable value. More recently, Gates [8] has made new estimates of the spectral distribution for air masses from 1.0 to 10.0, and his results are given in terms of both wavelength and wave number, the reciprocal of wavelength. He has also considered various concentrations of aerosols and water vapor, basing his calculations on the Johnson solar constant.

A useful set of probable solar radiation intensity data for clear days is to be found in the 1967 ASHRAE Handbook of Fundamentals [9]. These values were obtained by a computer program set up by D. G. Stephenson [10] of the Division of Building Research, National Research Council of Canada, using direct solar radiation data compiled by Threlkeld and Jordan [11] and an empirical formula developed by Threlkeld [12] for the diffuse radiation. The ASHRAE tables cover latitudes from 24 to 56 deg north by 8-deg increments. Similar data are given by Stephenson [13] by 2-deg increments for latitudes from 43 to 55 deg north. These tables give the solar altitude and azimuth (measured from the south) at hourly intervals, in addition to the intensity of the direct solar beam for the 21st day of each month. Data are also given for "solar heat gain factors" [9] which can readily be converted into the

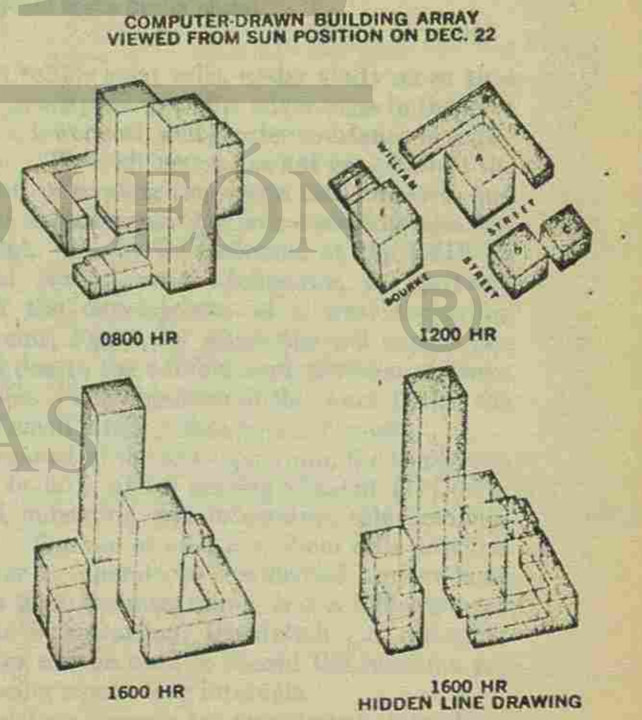

Fig. 1 Isometric views of Australian building complex as seen by the sun at 0800, 1200, and 1600 hr local solar time (CSIRO photo).

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[1] Numbers in brackets designate References at end of article.

[2] *Btu* = Btu/hr/sq ft.

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A WORLD PICTURE

intensity of the total radiation incident upon horizontal surfaces and on vertical surfaces facing in each of the eight principal directions. Equations are also given by which the intensity of the radiation falling on tilted surfaces can be estimated.

The Australians have made great strides during the past decade in many aspects of solar energy technology, due in part to the fact that an economic incentive exists because of the lack of natural gas in that continent and in part to the fact that a team of ingenious and dedicated engineers has been set up under the leadership of Roger Morse in the Mechanical Engineering Division of the Commonwealth Scientific and Industrial Research Organization at Melbourne. Among their achievements is the development of a computer program (appropriately designated SHADE) by which isometric projections of building arrays can be drawn as they would be viewed from the sun's position. Fig. 1 shows a building complex now under construction in Melbourne as the sun would see it at 0800, 1200, and 1600 hr.

Solar Batteries

The silicon cell, now some 15 years of age, has proven to be a superbly reliable means for the direct conversion of solar radiation into electricity. Invented in 1954 by the team of Bell Laboratories scientists who also invented the transistor, the silicon cell has now been developed to the point where all of the permanent satellites and most of the long-range spacecraft launched by Russia and the U. S. during the first decade of the space age have used increasing large arrays of solar batteries. Originally used in the P-on-N version (the positive surface faced the sun), the first generation of solar cells was found to be susceptible to rapid deterioration from destructive solar radiation. Research conducted both in Russia and the U. S. showed that reversing the cell, thus placing the negative element in the sun-facing position, produced greatly superior radiation resistance. All of the cells being produced today are N-on-P type, although large numbers of P-on-N cells are still available from space-surplus dealers.

The current status of photovoltaic power technology was described in detail by Smith [14], who pointed out that high-quality cells (10–12 percent initial conversion efficiency) are now being manufactured in large numbers by three suppliers in the U. S. Cherry and Statler [15], in their paper on radiation resistance, list three more U. S. manufacturers and three in Europe.

Most of today's cells are 2 × 2 cm in area, with a thickness as low as 0.004 in. In full sunlight (using the Johnson solar constant of 140 mw/sq cm), a typical 2 × 2-cm cell will give a short circuit current of about 125 ma, an open-circuit voltage of 0.50 v (at 60 C), and a maximum power of some 42 mw. Deterioration due to electron bombardment is a serious problem for cells which are to be used on spacecraft which are traveling toward the sun.

The generation of significant amounts of power requires series-parallel connections of extremely large numbers of individual cells, with as many as 350,000 individual cells for the Saturn I workshop, and twice this number for future space stations. A major effort is now being made to produce larger individual cells, thus reducing the number of connections which must be made and improving efficiency by reducing the area occupied by those connections. Important reductions in assembly costs can also be accomplished. Fig. 2 shows an experimental array of 2 × 8-cm cells which will reduce by a factor of four the number of junctions which must be made, as compared with the conventional 2 × 2-cm cell which is currently in use.

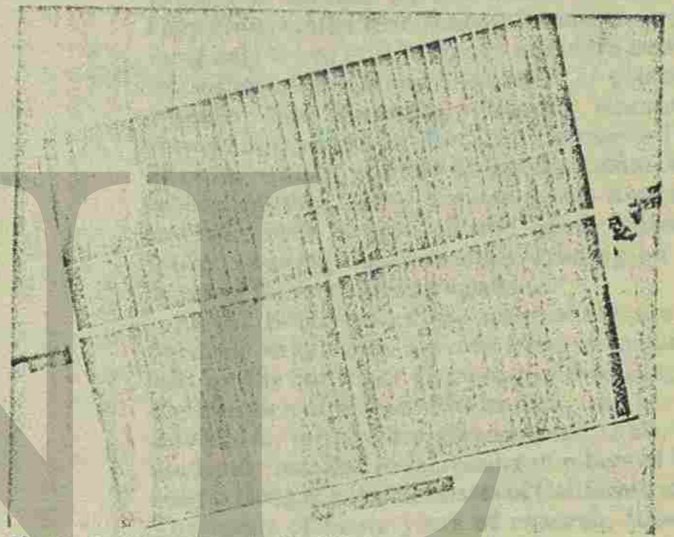

Fig. 2 Experimental solar "paddle," covered with 2 x 8-cm silicon cells (Goddard Space Center photo).

Cadmium sulfide solar cells, under study since 1954 for the U. S. space program, offer advantages in the form of larger area, lower cost, and greater resistance to radiation damage. Their efficiency has not yet attained the halfway point in rivaling the silicon cell, however, and their rate of deterioration due to moisture is also undesirably high. K. G. T. Hollands, at the CSIRO's experimental station near Melbourne, is currently working on the development of a heat-dissipating reflector mount, Fig. 3, by which the cell output can be increased due to the twofold concentration of direct solar radiation. The objective of this work [16] is the operation of small water pumps by solar power.

As a by-product of the space program, the silicon cell has proven to be a useful sensing element [17] for a self-powered indicating and integrating solar radiometer, Fig. 4. The use of nine 2 × 2-cm cells provides enough power to operate a commercial ampere-hour meter which does the integrating, and a milliammeter indicates the instantaneous irradiation. A recording millivoltmeter can be used to record the sunshine experienced during month-long intervals.

Solar simulators, discussed at great length at the 1962 ASME Annual Meeting, have now come of age with the

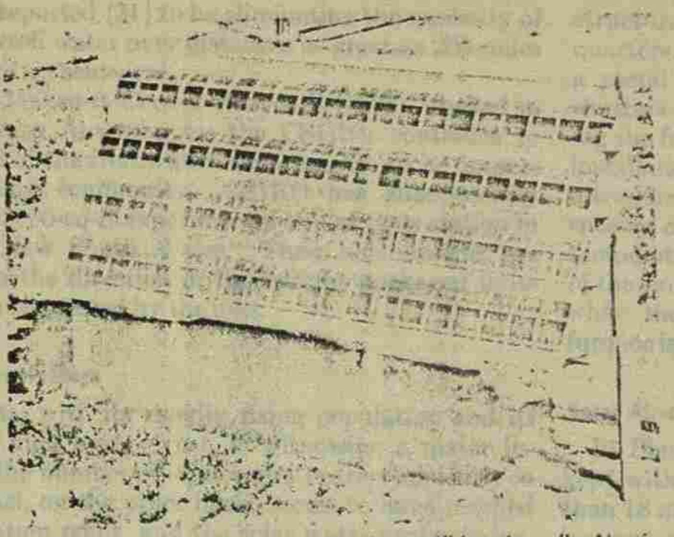

Fig. 3 Concentrator mount for cadmium sulfide solar cells. Aluminum wings double cell irradiation and help to dissipate heat (CSIRO photo).

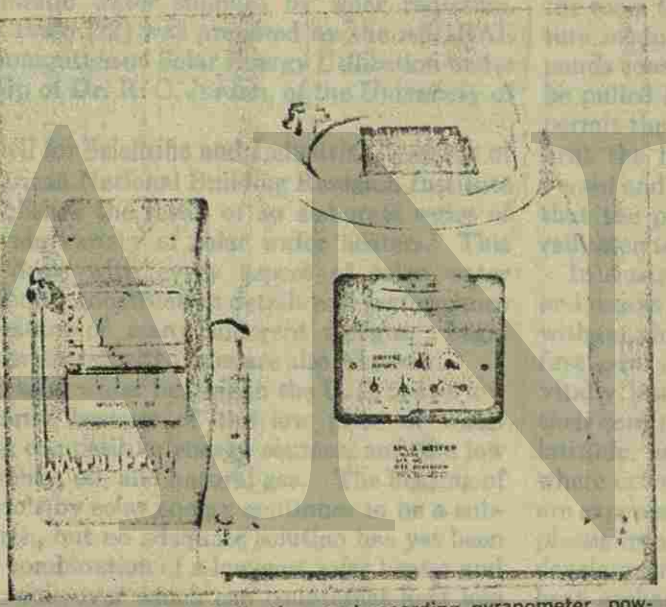

Fig. 4 Integrating, indicating, and recording pyranometer, powered by nine 2 x 2-cm silicon solar cells (Talley Industries photo).

construction of a gigantic vacuum chamber in which a full-scale space vehicle can be uniformly irradiated with simulated solar radiation from a battery of filtered xenon lamps. More compact versions of the same concept are available for terrestrial testing of solar cells and other components of space power systems.

Solar Stills

The production of potable water from salt or brackish supplies is the oldest application of solar energy to a technological process. In fact, the world's first solar still, and for nearly a century its largest, was built in Chile in 1872. Its area was 51,000 sq ft and this size was not exceeded until the 93,500-sq-ft, glass-covered seawater still was erected on the Greek island of Patmos in 1967. The design parameters of solar stills have been studied with great care by investigators in Australia, Greece, Israel, Russia, and the U. S. Battelle Memorial Institute [18] is currently preparing a detailed report for the U. S. Office of Saline Water covering all aspects of the design of solar stills. The report is expected to be made available this year.

The details of the Patmos installation have been reported by A. and E. Delyannis [19], who have pointed out in an earlier publication [20] that glass is to be preferred over plastic films as the covering material of large solar stills. Among the reasons given are the lower total cost of glass as compared with wettable fluorocarbon films, the greater resistance of glass to damage by wind and storm, its freedom from vapor permeation, pinhole leaks, and the electrostatic properties of plastic films which cause dust to adhere tightly, requiring frequent washing with precious distillate.

The total cost of the Patmos still is reported as $1.49 per sq ft of distillation area and its average output is nearly 7000 gal of fresh water per day. The 21,700-sq-ft still erected in 1969 on Nissyros cost $2.11 per sq ft. The Greek stills now embody the results of the experience gained from their first large still, the 28,600-sq-ft installation erected on the island of Symi in 1964. They are operated with shallow basins, the water depth being only 2 cm, or 0.78 in., to minimize excessive concentration of brine and formation of calcium sulfide crystals. One surprising difficulty encountered at Patmos is reported by the Drs. Delyannis [19] in the following words: "After lining the basins with butyl rubber sheeting during the spring, we were amazed to observe weeds, a type of wild grass, perforating the rubber sheeting and peacefully growing on top of it, enjoying the fresh air and sunshine."

At the other end of the scale in size are the small domestic stills which are now being manufactured and sold by the Sunwater Company of San Diego. Under the direction of Horace McCracken, who has labored in this field for many years, glass-covered, shallow-pan stills are being installed in increasing numbers of homes and resorts along the Pacific coasts of California and Mexico. The result of many years of research, these stills are provided with automatic water-feeding devices, Fig. 5, which will keep them supplied with the proper amount of seawater. With outputs from 2 to 200 gal/day, these

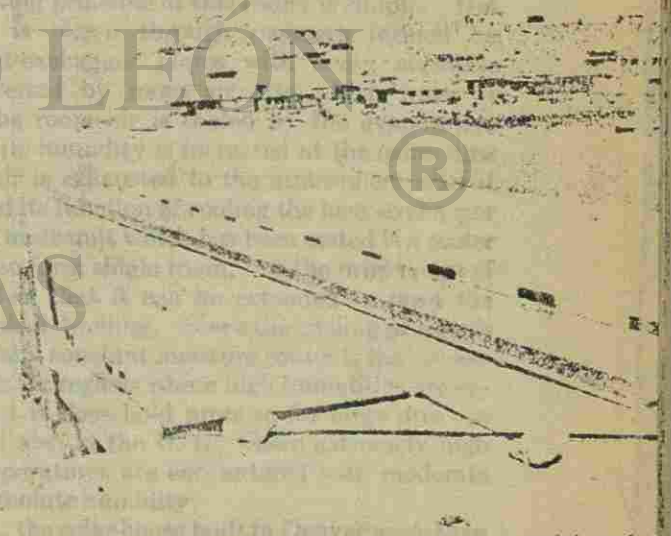

Fig. 5 Ten-gallon present-day solar still on a motel roof a Puertecitos, Baja California, Mexico. Prior to this installation, a fresh water used here had to be hauled 200 miles by land, sea o air (SEAWATER photo).

stills are reported [21] to be eliminating the necessity of hauling fresh water over distances as great as 200 miles at a cost of six cents/gal.

The 38,000-sq-ft Coober Pedy still (1966), erected in northwestern Australia by the CSIRO, continues to supply all of the freshwater requirements to an important mining community. CSIRO has subsequently erected a 5000-sq-ft experimental still at their station in Griffith New South Wales. Their new designs are moving in the direction of lightweight packaged units which can be erected by the user.

Solar Water Heaters

Australia, with its rapidly rising population and its relatively high energy cost, is witnessing a major increase in the number of solar water heaters currently in use. Israel, on the other hand, seems to have reached the saturation point, and the solar water heater industry there is on the decline. Several definitive publications have appeared in recent years on the technology of heating domestic water supplies by solar radiation. The first of these [22] was prepared by the ASHRAE Technical Committee on Solar Energy Utilization under the leadership of Dr. R. C. Jordan, of the University of Minnesota.

The Council for Scientific and Industrial Research of the South African National Building Research Institute [23] has published the result of an elaborate series of tests of a wide variety of solar water heaters. This publication deals with every aspect of solar water heating, including construction details and performance of water heaters of many different designs. Legal details for compliance with codes are also discussed.

Interest in solar water heating in the U. S. is at a low point, primarily because of the low price of water heaters using competitive energy sources, and the low cost of electricity, oil, and natural gas. The heating of swimming pools by solar energy continues to be a subject of research, but no adequate solution has yet been found to the combination of a low-cost solar heater and an effective pool cover which can counteract heat loss by evaporation and radiation to the sky.

Solar Furnaces

The first scientific use of a solar furnace is reportedly that of Lavoisier in Paris in 1774, who used "a glass lens as tall as a man for carrying out chemical studies at high temperatures." Nearly two centuries later, the first large solar furnace of modern times was erected under the direction of Dr. Felix Trombe at Montlouis in the Western Pyrenees. This furnace used a heliostat 30 ft square to reflect the sun's rays onto a concentrator made of 3500 individual plane glass mirrors which were mechanically deformed to create a paraboloid. The successful operation of this furnace has led to the construction of a vastly larger unit on a mountainside between the adjacent villages of Font Romeu and Odeillo. This location is reported [24] to be the sunniest place in France, averaging 250 clear days per yr.

Sixty-three heliostats are used, each containing 180 plane mirrors, 50 cm square, giving a total of 2835 sq m of reflecting surface. The concentrator consists of 9000 small plane mirrors, arranged to form a paraboloidal surface of 2500 sq m. It is supported by a 10-story structure which also houses the laboratory headquarters. The focal area of the furnace is contained in a metal enclosure which is fitted with stainless-steel shutters to control the amount of solar radiation reaching the focal zone. The principal objectives of the new installation are reported to be [25] production of large, ultrapure crystals by zone melting, preparation of highly specific compounds, and production of extremely high temperature refractory materials. The thermal power of the smaller French furnace is 50 equivalent kilowatts, while the rated power of the new and much larger furnace is 1000 equivalent kilowatts.

Solar Air-Conditioning

In Phoenix, Arizona, a prototype building has been kept within the comfort zone during a period of more than 18 months by the operation of a unique solar heating and sky-cooling system (ME, January 1970, pp. 19–25). The structure uses shallow ponds of water which are in thermal contact with the metal ceiling of the room to provide both thermal storage and temperature modulation. Horizontal plastic panels above the ponds constitute the roof of the building, and these can be pulled away from the ponds during winter days to permit the rays of the sun to warm the ponds and thus heat the house. In the summer the situation is reversed and the insulating panels are removed at night so that the ponds can be cooled by evaporation and by radiation to the sky [26].

In Australia much effort has been expended on ways and means to produce cooling by other natural processes without the use of refrigeration, which is expensive in first cost and in running cost. The Australians are vitally interested in natural air-conditioning, because their continent lies mainly between 10 and 35 deg south latitude, and it is characterized by vast desert areas where extremely high temperatures and low humidities are experienced. Experiments with rock piles and with plastic rotary regenerators are reported [27], and a new development of a unit air cooler, employing a plastic heat exchanger with evaporatively cooled plates, was reported recently.

The operating principle of this cooler is simple. Hot outdoor air is blown through passages formed by dimpled heat-exchanger plates with every alternate passage traversed by room air into which water is sprayed. The room air is cooled by the evaporative process, but its humidity is increased at the same time and so this air is exhausted to the atmosphere after it has performed its function of cooling the heat-exchanger plates. The basic unit which has been tested is a cooler suitable in size for a single room, but the originators of this system feel that it can be extended to meet the needs of a typical dwelling. Since the cooling process is one of essentially constant moisture content, the process is not suitable for regions where high humidities are encountered, but it does hold promise for large areas in Australia and also in the U. S., where extremely high dry-bulb temperatures are encountered with moderate or even low absolute humidity.

In the U. S., the solar house built in Denver more than a decade ago by Dr. George Löf continues to operate satisfactorily, with most of its winter heat requirements being supplied by the sun. Similar results are reported for the solar houses erected near Washington, D. C., by Harry Thomason.

Interest in solar-activated absorption refrigeration continues at the University of Florida, as illustrated by Fig. 6, which shows the collector-generator used by G. L. Moore and E. A. Farber at the University of Florida Solar Energy Laboratory near Gainesville. Unfortunately, only limited financial support is available for work of this type, and so the results have been correspondingly meager.

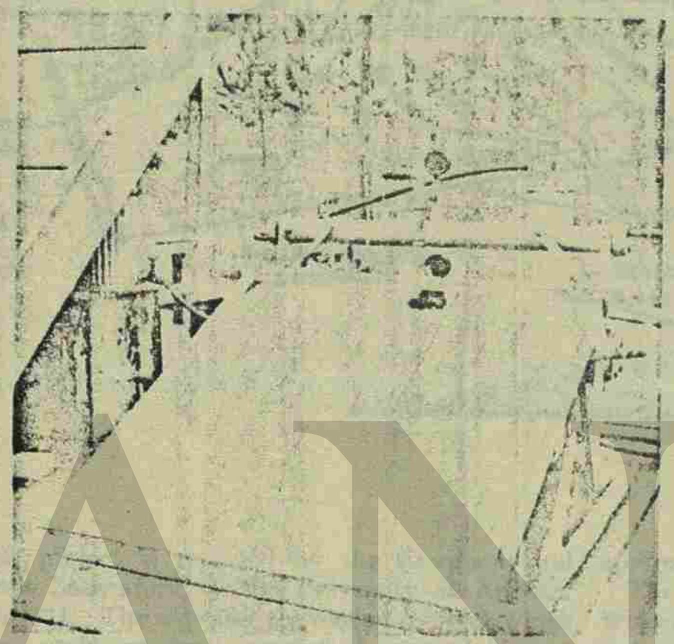

Fig. 6 Collector-generator used with solar refrigeration system at the University of Florida's Solar Energy Laboratory in Gainesville (photo courtesy of Dr. Gordon Moore).

Solar Power

As the need for larger power sources becomes apparent in the space program, interest has turned again to fluid cycles which can receive their heat from large solar concentrators and reject the heat which they cannot use to outer space by radiation. NASA is currently testing a closed-loop Brayton cycle [28] which uses a mixture of inert gases (helium and xenon) as the working fluid, with a high-effectiveness regenerator to transfer a large portion of the exhaust heat into the compressed gas. A 10-kw power plant using this system would be expected to weigh 3500 to 4000 lb, which is well within the capability of today's boosters. For energy storage when the spacecraft is in the dark, lithium fluoride would be used. For planetary probes traveling away from the sun, an isotope heat source is proposed. The closed-loop Brayton system is also though to be suitable for use under water and in remote Arctic regions.

For use in the much more distant future, Dr. Peter Glaser has proposed a novel space system in which two satellites, orbiting the earth in an east-west direction at an altitude of 22,300 miles would continuously convert solar radiation into electrical power and transmit this back by microwaves to receivers on the earth. For this purpose the solar concentrator would be approximately four miles in diameter, and a two-mile-wide antenna would be required on the earth [29].

In his paper Dr. Glaser gives forecasts of the energy requirements of the world for the year 2000, and he notes that these will strain the capacity of all of the conventional energy sources, as well as the nuclear power which is likely to be replacing fossil fuels.

Heat Transfer

No new developments in fundamental heat storage technology are reported, but ingenious new applications of well-known materials continue to be developed. Dr. Maria Telkes reports [30] the development of temperature-control systems for use in the long-range weather forecasting balloons which will be employed in the Worldwide Weather Watch. The balloons will circle the earth at 30,000 ft or higher for periods up to six months, and they will have an electronic communication system powered by solar cells and a storage battery. The information which they obtain will be transmitted to a satellite circumnavigating the earth nearly 16 times per day. Some thousands of such balloon stations will be in use continuously. At the altitude at which the balloons will travel, temperatures will range from −30 C in the sun to −60 C at night. The electric power output of the nickel-cadmium batteries in the power system will drop to zero at such low temperatures, and so the radiation from the sun must be used to warm the batteries.

The difficult problem of keeping the daytime temperature of the battery below 80 F, while the nighttime temperature remains above −8 F, was solved by using one of Dr. Telkes' heat storage materials, which has its melting point at −8 F and, during the daytime, can absorb enough solar heat to keep the battery temperature below the 80 F limit. To minimize heat loss by radiation at night, the battery tubes are surrounded by a spiral shield containing eight layers of Teflon FEP type-A film. The transmittance of this heat shield for solar radiation is nearly 0.70, as compared with 0.50 for eight layers of clear window glass, and 0.35 for eight films of 0.005-in. Mylar.

Since the balloons will travel at the altitude which is currently used by jet aircraft, they must be extremely fragile so that they will not damage aircraft windows or engines. The combination developed by Dr. Telkes is reported to meet that requirement, as well as the very stringent temperature limitations demanded by its components.

Basic Developments

No radically new solar developments have been reported in the past several years, but significant studies have been made of earlier discoveries. The honeycomb heat absorbers first proposed by Francia [31] have been subjected to intensive analysis with encouraging results. It has been found [32] that cellular structures, particularly of elongated rectangular shape, can perform three useful functions: (1) Suppress natural convection and thus form good insulators, (2) transmit thermal radiation which is directed down the axis of the cell, and (3) block much of the radiation which is emitted from the heated surface.

A significant change in direction of a major solar

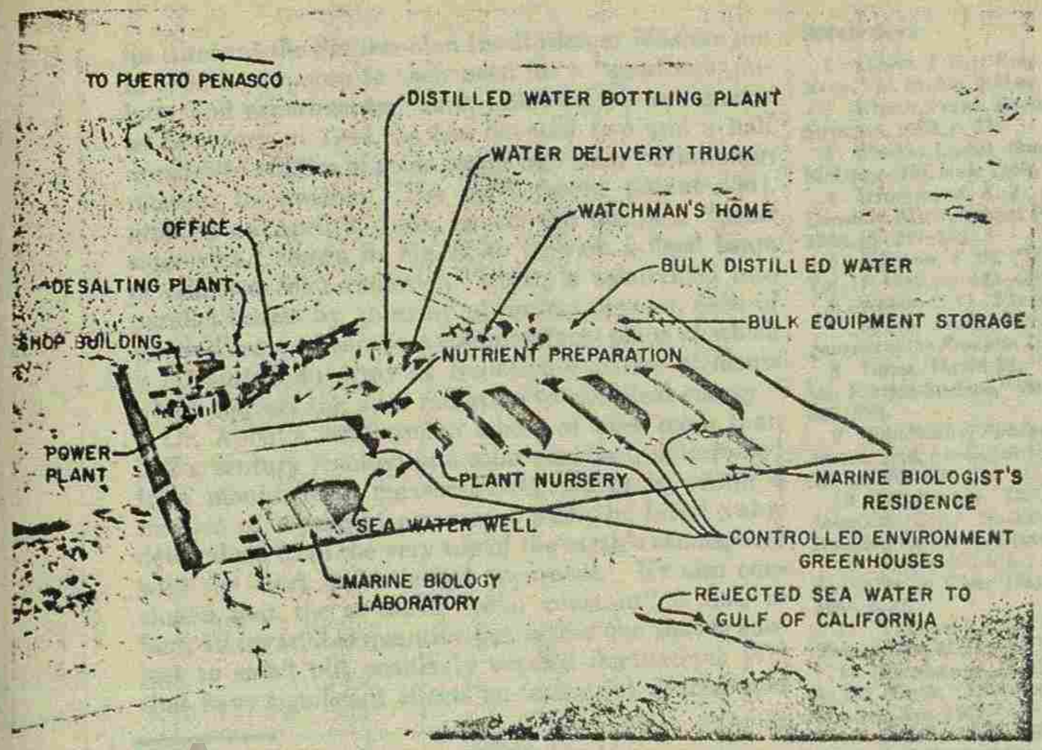

Fig. 7 Integrated plant at Puerto Peñasco, Mexico, produces fresh water, vegetables, and power, using seawater, solar radiation, and a diesel engine (University of Arizona photo).

research project is reported by the Environmental Research Laboratory of the University of Arizona, Tucson [33]. The seawater conversion research which has been underway for a number of years at Tucson and Puerto Penasco, Mexico, has been turned to a study of the growth of vegetables within controlled-environment greenhouses made of air-inflated plastic, Fig. 7. The sun's radiation makes the vegetables grow and energizes the solar distillation process by which the water which is transpired by the plants is condensed on the under surfaces of the greenhouse cover to be returned to the plant roots. Much of the heat required to produce fresh water from the available ocean water comes from the Diesel engine which is required to pump the seawater. In addition, the exhaust gases from the engine, after being cleaned in seawater scrubber , can be used to enrich the atmosphere within the structures with carbon dioxide, thus greatly accelerating growth of the plants inside.

This program, under the direction of C. N. Hodges and sponsored by the Rockefeller Foundation, gives promise of producing both food and water for isolated desert areas where the only present water supplies are either brackish or saline. A large installation is now being planned for erection at Abu Dhabi, a Trucial State on the Arabian Peninsula, 500 miles southeast of Kuwait. A grant of $3.16 million has been made by the ruler of this state to the University of Arizona to plan and construct an integrated power-water-food facility in his state. One of the goals of this program is to reduce the price of vegetables, which now cost $1.50/lb at Abu Dhabi, to something like 10 cents/lb, and to produce perhaps 2 million lb of high-quality food annually to supply the 40,000 people who live in Abu Dhabi. The complex to be erected in Arabia will be approximately ten times as large as that shown in Fig. 7.

The Solar Energy Laboratory at the University of Wisconsin, under the direction of Prof. J. A. Duffie and the leadership of Professor Emeritus Farrington Daniels, has been active for more than a decade in the field of solar energy utilization. The major financial support for this work has come from the Rockefeller Foundation and the Wisconsin Alumni Research Foundation. Their work has been devoted toward the classic objectives of meeting human needs for drinking water, cooking, house heating and cooling, refrigeration, and production of electric power for the operation of pumps. In a detailed report to the sponsors of this work [34], it has been pointed out that the difficulties which still confront workers in this field are both sociological and technological. Apparatus which appears simple to a competent American technician may pose formidable problems to those in foreign lands who have never confronted anything remotely technical. Customs which have evolved through millenia are not altered quickly and tradition stands in the way of change in any aspect of life in primitive cultures.

The philosophy of the work at Wisconsin has shifted [35] in response to increasing knowledge of the problems which confront the solar researcher and in recognition of the fact that solar devices will only gain acceptance if they do a necessary job cheaper and better than competitive apparatus. Messrs Löf, Close, and Duffie conclude [35, p. 250]: "With the exception of salt factories, water heaters, stills, and solar cells, solar processes and devices are not yet sufficiently economical, reliable, or convenient to meet real needs."

The dean of the solar energy movement throughout the entire world is undoubtedly Dr. C. G. Abbot who is, at this writing, in his 98th year. Dr. Abbot began his career at the Smithsonian Institution of Washington in 1895 in response to their need for a "good manipulator and experimenter" and, following his retirement as Secretary in 1944, he has devoted two and a half decades to studies of solar power and solar radiation in relation to weather. His most recent patent [36], granted on April 2, 1968, covers the use of a "polar siderostat," shown in Fig. 8, to provide a fixed beam of reflected solar radiation "which is subdivided into parallel beams by an array of optical devices, each of which directs a beam to a common focal plane at which is supported an array of radiation-sensitive elements which convert the solar radiation to electrical energy."

Dr. Abbot's Smithsonian labors of over more than half a century resulted in a solar constant, determined from mountaintop measurements, which is within a fraction of a percent agreement with the latest value determined from the very top of the earth's atmosphere with the most sophisticated apparatus. He also concluded that the so-called "solar constant" is not, in fact, an invariable quantity but rather one that is subject to small but positively verified fluctuations [37] that have significant effects on terrestrial weather and temperatures. Unfortunately his series of solar-constant determinations was terminated upon his retirement and it is to be hoped that a major objective of any permanent manned satellite will be the resumption of absolute measurements of our one basic source of energy and life, the radiation from the sun.

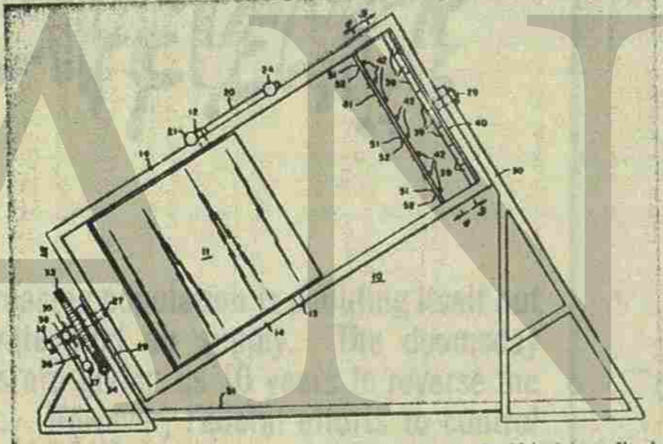
Fig. 8 Polar siderostat used in 1968 by Dr. C. G. Abbot to reflect solar rays throughout the entire year upon a battery of helio-electric generators

The Solar Energy Society, with headquarters on the campus of Arizona State University, Tempe, continues to search for uses of solar energy utilization by publishing its quarterly scientific journal, "Solar Energy," under the editorship of Dr. A. J. Drummond of the Eppley Laboratories. The 1968 meeting of the Society, held at Palo Alto in October, was well attended by representatives of a dozen countries. The 1970 meeting was held, appropriately, March 2–6, at Melbourne, Australia, which is the location of much of the most significant work currently being done in solar energy utilization. The president of the Society for the past two years has been Dr. P. E. Glaser, Mem. ASME, of Arthur D. Little, Inc., Cambridge, Mass., and president for 1970–72 is Roger Morse, head of the Mechanical Engineering Division, CSIRO.

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POLLUTION—POLITICAL EXPEDIENCY AND TECHNOLOGICAL COMPETENCE

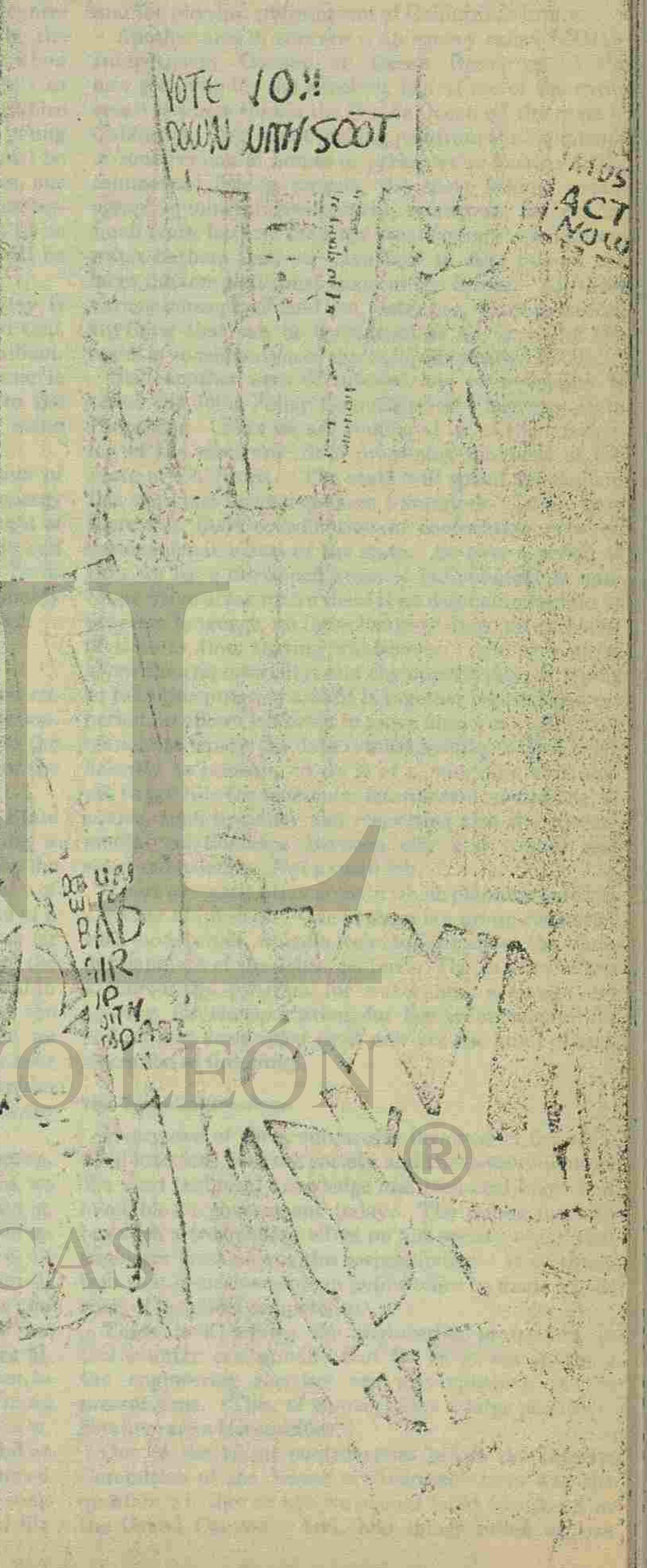
Our increasing population is polluting itself out of its water and air supply. The doomsday prophets are giving us 10 years to reverse the damage. However, Federal efforts to control pollution have begun to produce a considerable volume of legislation, but many decisions are being based on political expediency rather than technical competence. Hence, it is vital that engineers become involved in making those decisions that will determine the directions and development of our society.

ED REINECKE, Lieutenant Governor

State of California
Sacramento, Calif.

The changing environment of California can be divided into four basic areas: air, water, land, and urban society. Hence, it is not just a question of the conditions of the air quality in Southern California or the water quality. Rather, it is a total program involving people, from the universities to the ghettos and all of the things that they look for in their quality of life. The engineers of today and tomorrow must become vitally involved in this. We have the building blocks but we must learn how to use them, how to put them together.

Values are on the line; values are being critically



analyzed. And the young people of today recognize that what we do with society today is going to be the world they have to live with and maintain when they become adults. That's the reason they are so outspoken, and the reason they are willing to criticize and condemn. If we are to offer a legacy to the young people of today, to the world of tomorrow, we must be willing to scrutinize our own assessment of values, our own assessment of technology today, our own assessment of ourselves and our efforts in this society, to be sure that what we do leave is something that will be valuable tomorrow.

For example, the population of California today is about 20 million. It is conservatively estimated that by the year 2000 this population will be 38 million. This is a pretty drastic increase when you consider it took roughly 200 years for California to grow to the 20-million level, and in only 31 years we are going to virtually double that population.

Recognizing, also, that the rate of consumption of consumer products, of goods, of services, and of energy are going up far faster than any linear development of the population itself, we can say that the goods and services required to support the kind of life we know today at the end of that 31-year period will probably be five times the goods and services required today.

Plan Today for Tomorrow

Several of the responsibilities of the Office of Lieutenant Governor are concerned with the planning function. Therefore, all of this is very relevant, especially to the young people and certainly to the people who are the doers, the makers, the designers of today.

One such responsibility is jurisdiction over the State Office of Planning. The State Office of Planning is charged with devising statewide plans, not just for the sake of conformity with federal law, but for the sake of developing that kind of a population and that kind of a quality of life we are really looking for in that year 2000. An interesting outcome is the fact that the young people are saying today, we're not interested in talking about air pollution, we want to talk about the root causes: people. We want to find out how we can do something about population control. We hear repeated statements, drastic statements of how population should be controlled as a means of dealing with our expanding society and population.

Assuming we are going to double the population, we need to think in terms of the quality of life we are looking for, the type of dwelling, the type of living, whether we want to build industrial cities and residential communities far separated from the industrial complex, connected perhaps by some form of rapid transit, or whether we want to live in high-rise apartments and building structures such as we see in some parts of our cities today. Whether we want to go completely rural, whether we want to decentralize or whether we want to centralize. There are many considerations that must be taken into account *now*, not a few years from now. It's not something that we can go on doing a little bit at a time. Plans must be made and plans must be carried out. This is why the State Office of Planning has such a vital function in terms of shaping the quality of life and the physical environment of California's future.

Another area of concern is an agency called ICOR—Inter-Agency Council on Ocean Resources. We're now planning for the effective, logical use of the entire ocean resource that is the Pacific Ocean off the coast of California. We're not looking just from the standpoint of construction of homes or parks, we're looking at the commercial fishing aspects, the sport fishing, oceanography, mineral development, recreation, harbors for small craft, harbors for large ocean-going ships, deeper-water harbors than we have now to take care of the large tankers that must come in the future. All these various concepts of land use, water use, water pollution, anything that can be considered at all, is within the realm of consideration of this little office called ICOR.

Still another area of interest and responsibility is called the Joint Policy Committee on Electronic Data Processing. Here we are looking at all of the interlacing of the electronic data processing functions of the State of California. The state will spend $55 million this year just operating those computers. In the past there was little coordination or cooperation between various departments of the state. So over a period of time we have developed areas of individuality in non-cooperative areas where there is no common program or program language, no interchange of data, no exchange of time or time sharing whatsoever. And now we're given the responsibility, and the opportunity, of trying to take this program and fit it together over a five-year period, to allow California to move ahead in an effective manner to handle the data it must handle, to do it as efficiently as possible, to do it at a minimum cost, and yet to provide the maximum information, protecting, of course, confidentiality and respecting also the governmental relationships between city and county and state and federal. Not a small job.

There are many other areas in which planning becomes a matter of interest. One of them is a group concerned with model cities, wherein we're talking about the whole development of the urban centers. This is more or less a short-range program for water and sewerage, for housing, for transportation, for law enforcement—the factors that are needed right now are the areas of consideration of this group.

The Technical Interface

Every one of these subjects is involved in the technical interface between society and the design function. We need technical knowledge and technical know-how available to government today. The public function has such a tremendous effect on our society today that engineers must accept this responsibility. It is important that decisions made in public office be made on the basis of technical competence.

There is a service the engineering professions in this country can provide that far surpasses anything the engineering societies are accomplishing at the present time. This, of course, offers a large challenge. But here are a few specifics:

One of the major controversies before the Interior Committee of the House of Representatives was the question whether or not we should build two dams in the Grand Canyon. And, had things rolled on, we

The Towne Lecture

The Towne Lecture is in honor of Henry Robinson Towne, President of the Society in 1889, whose paper in 1886 on "The Engineer as an Economist" initiated the flow of valuable Society contributions on scientific management. The Towne Lecture gives opportunity for an outstanding leader in the field of management, economics, or business to reveal his experience—preferably related to the scientific method in industry or business.

would have had the authorization for those two dams today, but for the fact that there was one conservationist, Representative John Saylor of Pennsylvania, and one engineer, myself, on that committee. The two of us took on the task. He took it from the conservation point of view; I took it from the engineering and the economic point of view, and we analyzed these dams backward and forward. We found out what they would do and what they wouldn't do. And when we could not get adequate answers from the Department of the Interior, we had to spend nights generating the data. Without getting into the details of what went on with those dams, the mere fact there was someone on that committee who could ask technical questions, and when answers were provided, could ask follow-up questions, and someone on that committee who was not forced to accept blindly whatever was offered to him by the representatives of the Administration, was to a major extent what made it possible for us to see that legislation in a different light. As you may know, we passed that legislation but neither dam was included. Here was the possibility of spending close to a billion dollars to do a job that would not have been feasible. Later it was admitted that it was a very marginal project and that they probably couldn't have done it.

Another specific example: The Air Quality Act of 1967 was before Congress. It was proposed by the Secretary of Health, Education, and Welfare that there would be one national standard, a maximum standard, for all air quality in the U. S. Logic and reason don't agree that the same air standards should prevail in northern Idaho as there should be in Los Angeles. It became a fight on the floor of the House. Since I was the only engineer from California, I was given the opportunity to lead that fight. We were able to convince the other members of Congress there were considerations that dictated more strict standards for California, and as a result we were able to win the amendment which gave California the right to establish air quality standards more strict than the national standard which the Secretary wanted to impose. Simply because one member, an engineer, could explain words like carbon monoxide, carbon dioxide, the oxides of nitrogen, and hydrocarbon, was one of the reasons California is now establishing more stringent air standards. Had we not won that particular amendment, California would be restricted from doing anything further about her own air quality unless the national standards were also raised.

So you can see the tremendous impact of a little bit of technical competence in such a situation.

The Engineer's Role

It is important, therefore, that ASME, for example, not be satisfied just with the excellence of a particular design or a mechanical concept, or of complete mastery of the knowledge and laws of physics and materials, but to recognize it has a public responsibility that goes as far or farther than technical competency. If ASME doesn't accept this responsibility, other parties will—and those other parties may not have technical competence. Those other parties may make decisions based on political expediency rather than on logic. This is one of the real conflicts prevalent in governmental circles today. It's not enough for governmental bodies to be able to hire excellence in technology. It's mandatory that governmental bodies also involve and have technical competency in making the decisions that determine the direction and development of our society.

ASME should start something new—a public affairs program that will, for one thing, enhance and improve the image of the engineering profession. All too often we are talked about as the fellows with the bow ties, the saddle shoes, and the slide rules. That's not really the case, but the public still sees the engineer as a very sophisticated technician and nothing more. He must be recognized as something far more than just a technician.

Beyond that, ASME should develop programs to involve its members—particularly the young people coming out of schools that are student members—in becoming interested and involved in governmental affairs, even if it means contributing some time to your city council, or your county board of supervisors, or whatever level of government might be available or accessible. This kind of service is necessary. The values which you can contribute will not only do a great deal to enhance the future of the engineering profession, but will do a great deal to enhance the quality of the society in which you live. This involvement, plus perhaps the personal involvement of yourselves as candidates for the highest possible level upon which you can serve in public life, will become a matter of awareness in your own mind and in your own evaluation of your function in life, to make it possible for us to find in the long run that quality of life we seek.

In short, engineers should be advocates of logic and reason in governmental circles, rather than sitting back and remaining in staff positions or in the position of critical analyst after a project has been accomplished.

If, in fact, all the technical societies can move together in this regard and bring forward the rational use of our technical competence, then we can find that quality of life, that environmental control, we are looking for. If we move ahead only with the idea in mind of building bigger bridges, bigger steam shovels, or faster cars or taller buildings, we will miss the mark; and we will miss a part of that public responsibility which the mechanical engineer should exercise.

DESIGN OPTIMIZATION USING COMPUTER TECHNIQUES

Designing an aircraft wing? Here's a unique approach to the optimization of the wing structural box for static loads. The technique employs the latest developments in structural synthesis and analysis and is applicable for both conventional and composite materials.

A. D. MAYFIELD[1]
General Dynamics, Fort Worth, Texas

Scientific computers have long been used in the design and analysis of aircraft wings. However, the method reported herein employs the use of the computer from the basic preliminary lines definition through the stress analysis of the wing structure, with a minimum of human intervention and effort.

Fig. 1 illustrates this optimization process and includes the steps discussed in the following. Wing lines data are generated through the use of an APT procedure which computes the three-dimensional geometry and enters this data on punched-paper tape. This tape, in turn, drives an automatic drafting machine. The geometric data for the structural box section is used in preliminary structural sizing procedures to rapidly evaluate various construction types and spar arrangements. This narrows the selection, such that a selected design can be further examined through the use of a design synthesis procedure which performs a rigorous design optimization of the structural box. The structural data from this design synthesis is then fed into a finite-element procedure which automatically sets up the structural idealization using a methodology similar to that employed in the APT wing lines procedure. This produces a double-precision, linear stress analysis of the wing box and an internal loads distribution, as well as the deflected shape. Depending on the degree of detail desired in the particular study, the design may be further refined through the use of an individual panel design option of the synthesis procedure, or the design process may be stopped at the completion of the analysis.

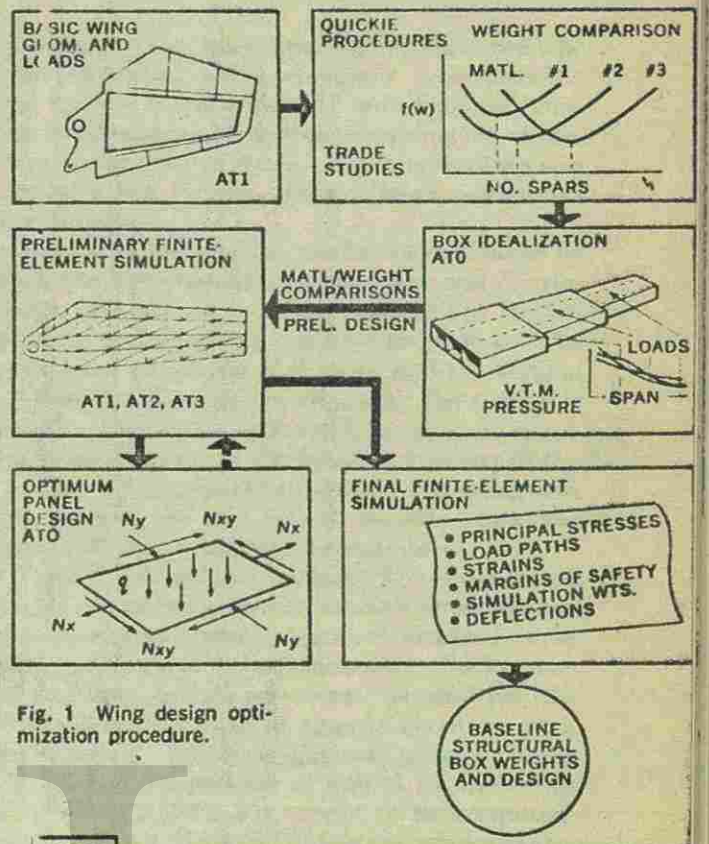


Fig. 1 Wing design optimization procedure.

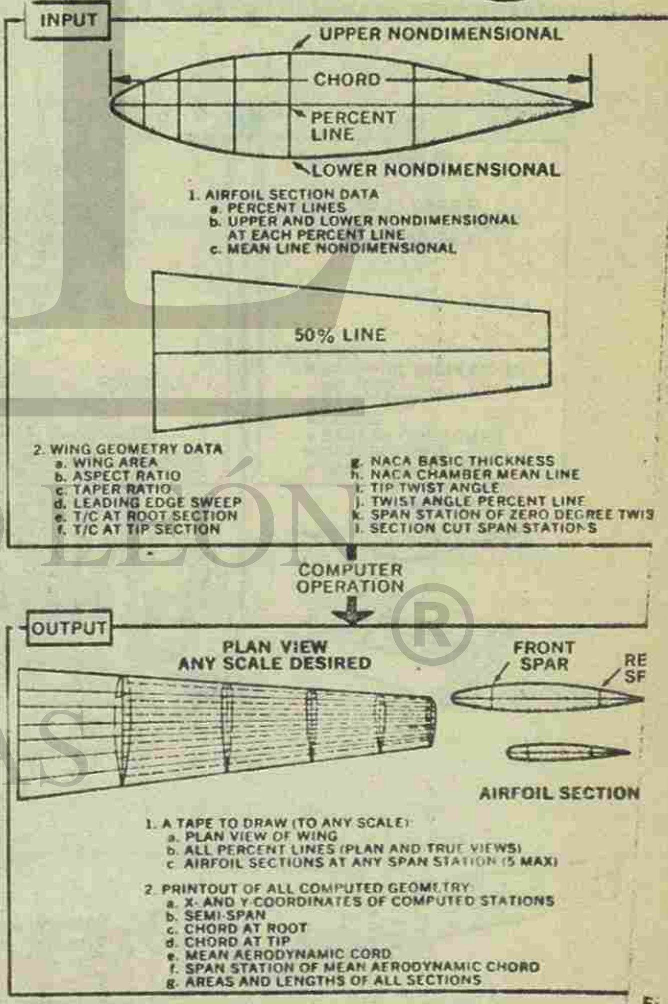


Fig. 2 APT computer procedure.

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[1] Project Design Engineer.

Based on a paper contributed by the ASME Design Engineering Division.

APT Procedure

The APT procedure is a generalized program for deriving the numerical data for defining a set of wing lines through the use of a numerically controlled drafting machine. This procedure can handle any wing shape for either variable or fixed wings. Also, it will accommodate wings with different airfoil sections at the root and tip, as well as different thickness-to-chord ratios at root and tip. In addition to these variables, the wing can be both twisted and cambered.

Basic computation is performed by the use of an IBM 360-65. Input to the program is shown in Fig. 2, and includes wing area, aspect ratio, thickness-to-chord ratio at the root and tip, airfoil coordinates at the root and tip, camber and twist, if any, leading edge sweep, front and rear spar location, pivot pin location, if it is a variable-sweep wing, and span stations at which section cuts are desired.

In addition to computing the three-dimensional data and preparing a punched-paper tape for driving a numerically controlled drafting machine, the procedure also computes the cross-sectional and wetted areas of the airfoil section, as well as the cross-sectional area of the structural box between the front and rear spars. This data is presented in conventional printed-paper formats. The information is also available in punched cards or in magnetic-tape form for direct links with computer procedures.

The information from this procedure, either from the printed data or the lines drawing, is then used in simplified structural sizing computer procedures to examine various combinations of materials and construction combinations, as well as evaluating the effects of varying the number of spars. These procedures size the structural box rapidly, using a basic section-by-section approach.

The input data includes the number of sections to be examined, the box cross-section geometry and distributed shear, moment, and torque loads at the respective stations, and pertinent material properties. The covers are sized on a basic M/h basis, and the vertical shear is distributed evenly to all spars; the torsion is distributed to the cover panels and front and rear spars. A rough check is made on the buckling capacity of the upper cover. It is possible to specify a bending and torsional rigidity, EI and GJ, if desired, which the procedures will use as additional constraints.

The output information contains the dimensional data of the structural elements at each cross section, including interior and exterior spar web thickness, spar cap areas, tension and compression cover thicknesses, rib web thickness, and rib cap areas. In addition, the weight in pounds per inch of span is given for each section evaluated. These weights are given in terms of the individual components as well as for the entire section, allowing a total box weight to be computed. Further, the section EI and GJ values are computed and printed.

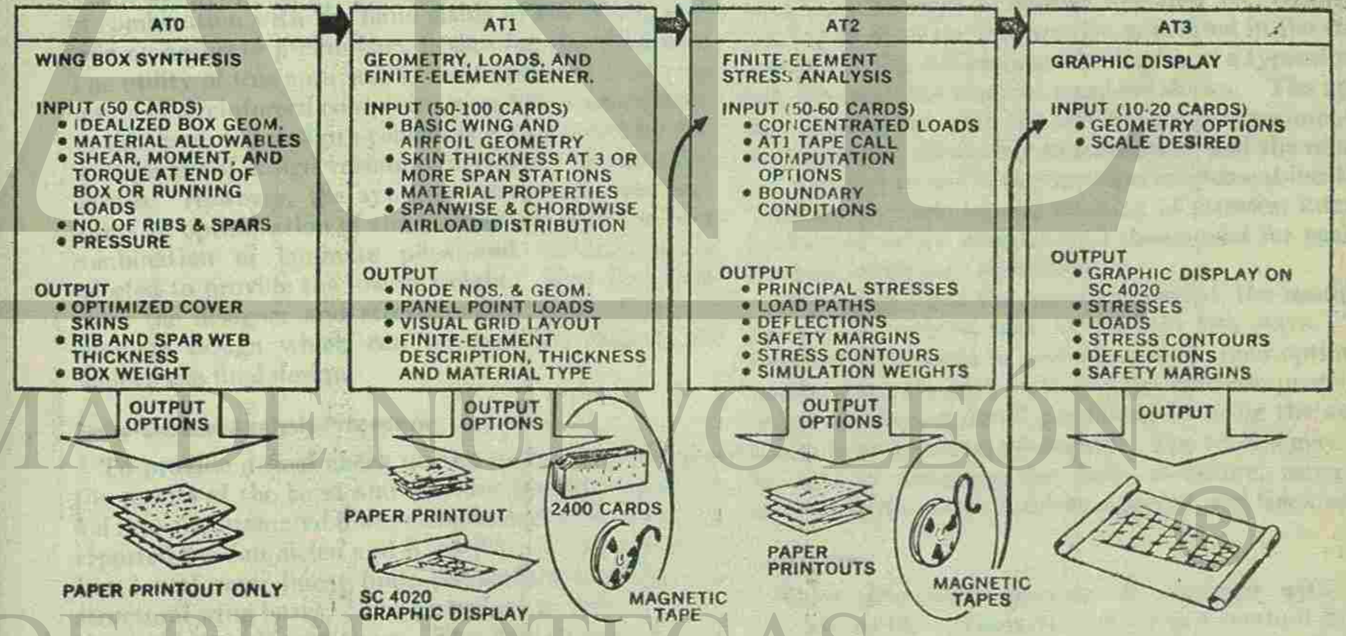

Fig. 3 Wing box synthesis and analysis technique.

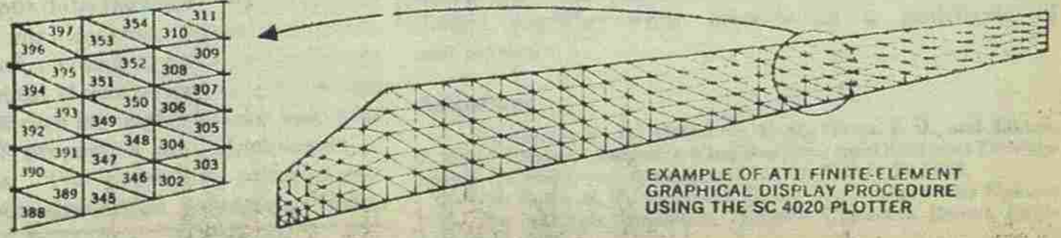

Fig. 4 Wing finite-element simulation.

The data from these procedures are then plotted in terms of box weight versus the number of spars, thus allowing a rational selection of the number of spars and the arrangement. Also, this information may be compared between different material and construction types to get a close idea of the relative weights.

Once rational selections have been made on construction types and spar arrangements, the selected structural arrangements are then examined in considerable depth through the use of a structural box synthesis procedure reported by McCullers and Waddoups [1].[2] Working with a set box geometry, loads, and spar arrangement, this program will simultaneously optimize the wing box to three distinct load conditions, including constant shear, constant torque, linear bending moment, and internal pressure for each load condition. It is also possible to design the compression cover only; in this mode, the loads may be input as running edge loads (N_x, N_y, and N_{xy}) and the pressure distribution (Q). The program has a built-in anisotropic plate analysis procedure using an assumed mode analysis. In either option, this procedure then develops an optimum design considering 18 design variables. The results from this procedure provide a very good comparison of the different material concepts. The weights are based on optimum load-carrying material only and exclude nonoptimum considerations for edge concepts and concentrated loads, which are usually added through normal hand computations.

The designs generated in the optimization procedure, in combination with the hand sizing of the edges, provide an accurate preliminary design for the wing box. The utility of this approach is most apparent when the design of a reinforced composite wing box is considered. In this case, the design problem is complicated by the multiplicity of design variables introduced by the composites. However, the synthesis procedure also performs an optimization of the laminate in that the best combination of laminate plies and orientations is selected to provide the lowest weight. This then provides the designer and stress analyst with an initial laminate design which can be modified slightly to achieve the final design.

Finite-Element Analysis Procedure

To provide a final check on the preliminary design, the results of the hand and machine computations are fed into an automated finite-element analysis procedure reported by Van Siclen and Reed [2]. This procedure, Fig. 3, performs a linear, finite-element stress analysis of structural wing boxes. The procedure is comprised of three sequential operations. The first procedure is a geometry generation scheme which automatically sets up the simulation of the structure to be analyzed in the second step. Less than 100 cards are required as input data to this procedure. Input data includes: airfoil geometry at the root and tip, spar locations, rib locations, material types to be analyzed, element types to be used in the simulation (bars, constant stress triangles, etc.), shear moment, and torque curves for each of three load conditions, and material properties and thicknesses at discrete span stations. The procedure subsequently generates the wing box simulation geometry, “panel points” each of the three load conditions, and assigns the thickness and stiffness values to the individual elements.

The second step requires approximately 20 input cards defining procedure options and additional discrete concentrated load points. This procedure performs a linear, finite-element stress analysis of the wing box using techniques reported by Blacklock, Richard, and others. The output data can be in the form of printed output, punched cards, or magnetic tape. This data includes node point deflections, internal load distributions on each element, including N_x, N_y, and N_{xy}, stresses on each element including $_x$, $_y$, and $_{xy}$, safety margins, and a weight estimate based on the weight of the structural simulation. As an option, the procedure has the flexibility to examine each element for each of the three load conditions and to ratio the element thickness up or down to get a closer margin of safety. This procedure will analyze all wing types including fixed and variable sweep, twisted and cambered. It also accommodates diverse structural arrangements having both spanwise and chordwise skin thickness variations. Upper and lower skin thicknesses may vary, and both chordwise and spanwise load variations are permitted. The procedure is general enough to be used on any structural box which may be simulated using constant-stress triangles for skins, quadrilateral elements for webs and bar elements for cap members.

The final step in this procedure utilizes the Stromberg Carlson 4020 Computer-Recorder to graphically display most of the information generated in the stress analysis. Fig. 4 illustrates the display of a typical wing box skin with the element numbers shown. The upper and lower skins, with the element grids superimposed, are displayed alternately in succession, and the numerical data is printed in the appropriate element location. The display includes the printing of stresses, internal loads, and safety margins and thicknesses for each of the load conditions simulated.

Depending upon the accuracy desired, the results of this stress analysis may be used in two ways. The results may be used to perform an even finer optimization by using the plate option of the synthesis procedure or by performing detail panel studies using the anisotropic plate buckling procedure. The results may also be used in designing the detail structure, using the internal loads, stresses, safety margins, and thicknesses.

Conclusion

These procedures provide the designer with new latitude in the optimization of wing structural boxes. The procedures have been automated and linked to the extent that they are easy to employ and provide a reduction in both time and laborious preparation of detail data, thus allowing the engineer to establish his design rapidly, while considering a multitude of candidates.

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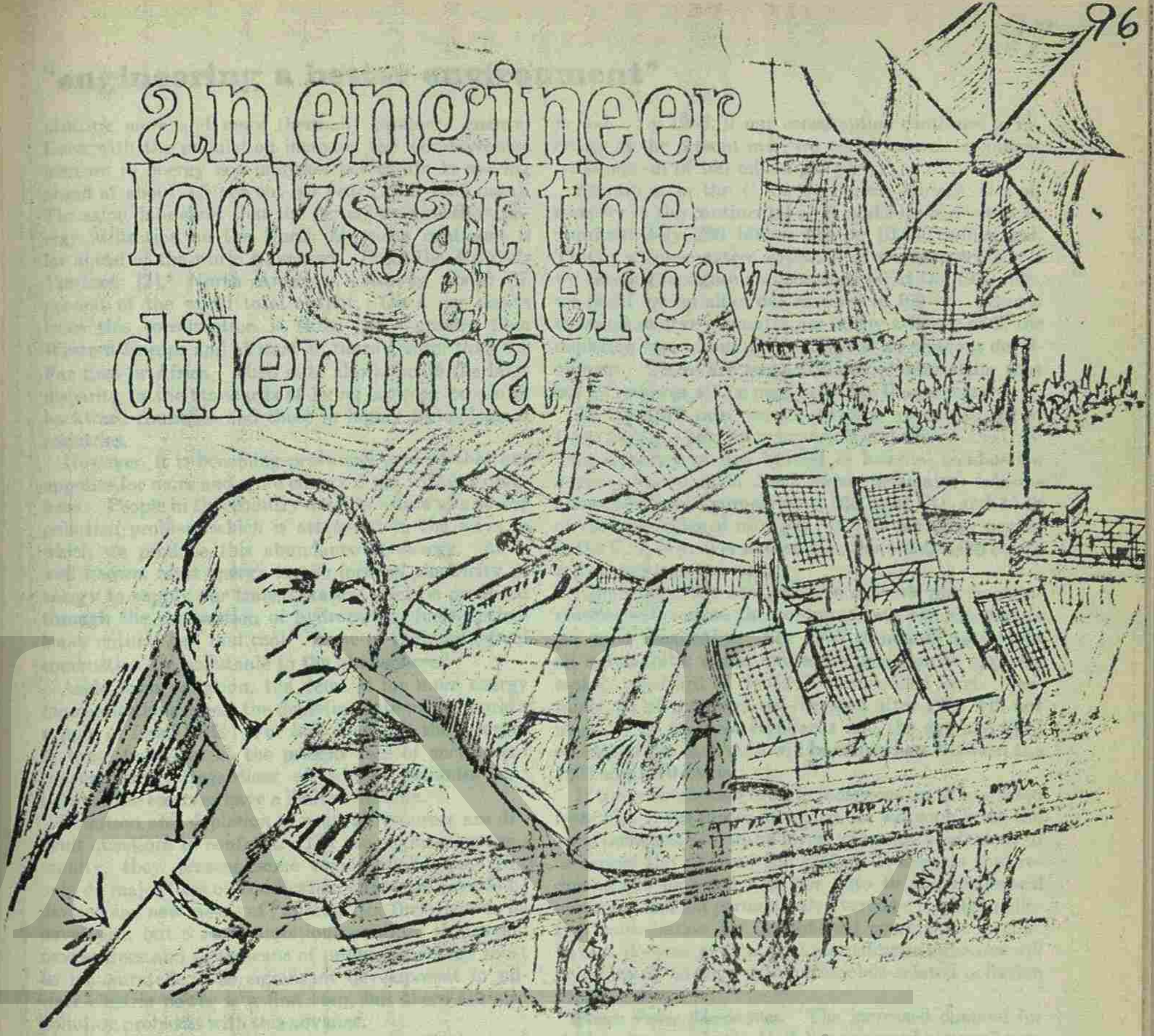
an engineer looks at the energy dilemma



The demand for energy is growing at such an accelerated rate that the attendant problems of pollution and fossil fuel supply depletion point to an urgent need for revision of engineering priorities before making critical decisions for the future. Development of nuclear power, more pollution-free sources of energy, and new concepts of transportation are challenges for today's engineers.

ROBERT W. GRAHAM[1]

THE ESCALATING consumption of energy by the world population is a topic currently receiving widespread attention in the news media. Technical journals, newspapers, and popular magazines alike have been carrying stories dealing with many aspects of the problem. Despite this unusual interest it is we mechanical engineers who really need to take a more serious look at the problems of meeting future demands for energy production. We are the professional group which will be most responsible for making critical decisions affecting the future in this area. Certainly, this has been our role in the past.

Decisions for the future will have to be made on new and different ground rules from those of the past. Coming at a time when ASME is reexamining its goals and priorities, it seems appropriate that we similarly devote much attention to energy production and utilization. Such review will necessitate major revisions in engineering priorities.

All of the information sources show that man is

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utilizing more and more thermally produced energy. Even with the population increase, the world-average increase in energy consumption per capita is moving ahead at about 3.5 percent per year (1963–1966 data). The same data show that the per capita growth in energy utilization on the North American continent is far ahead of the world's average. From the *Minerals Yearbook* [2],[2] North America consumes about 37 percent of the world total output. On a per capita basis this consumption is three times greater than Western Europe and at least 30 times greater than the Far East or Africa. Such data also indicate the huge disparity in the standards of living between people in backward countries and those in highly technologized countries.

However, it is becoming pressingly evident that our appetite for more and more energy is not without problems. People in this country are now aware of a severe pollution problem which is attendant to the ways in which we produce this abundance of energy. As is well known, most energy in the form of electricity or energy to supply our transportation needs is produced through the combustion of hydrocarbon fuels—petroleum, natural gas, and coal. Some of the products of combustion are pollutants to the atmosphere.

Aside from pollution, the demand for more energy raises questions about the depletion rate of the world's supply of fossil fuels. For how long will the reserves of these fuels last at the present rate of accelerated consumption? Regardless of whose estimates one believes the reserves have a limited lifetime.

Pollution and depletion of natural resources are difficult questions to confront. For the engineering community, they present some major challenges. Not only do major fixes on combustion hardware have to be devised and new means of "mining" the fuels have to be developed, but a more ambitious program to develop new sources and new means of producing energy must be inaugurated. The significant development in nuclear electric power is a first step, but there are also pollution problems with this advance.

Despite immediate efforts to control pollution and conserve fossil fuels, the development of new energy sources is imperative. Several new concepts have application in the areas of transportation and electrical power generation. But, new means of producing energy will not be without their concerns in creating new ecological and conservation problems. Any thermal system that can be conceived will involve losses and wastes of some sort. The second law of thermodynamics guarantees that there will be some kind of pollutant waste to deal with in any system.

Trends in Energy Consumption

The United States. The trends in the utilization of energy for transportation and electrical power consumption in the U. S. are evident from an examination of Figs. 1 and 2 [3]. The data are staggering in magnitude, and even more staggering in their extrapolation to the future. Consumption of gasoline and diesel oils has grown from 40 billion gal per yr in 1950 to 78 billion gal per yr in 1967—or almost double in that short time period. By 1980, if our consumption continues to increase at the present rate, we could exceed an annual consumption of 100 billion gal per yr.

According to the U. S. Geological Survey, the oil reserves in the continental U. S. and Alaska amount to approximately 200 billion bbl or 10,000 billion gal. This is a conservative estimate of these reserves. If we accept this figure and consume oil at the 1980 rate, we could use up all of our reserves in 100 yr. Even if these oil reserve estimates are off by a factor of 2, the depletion rate of our oil resources is an ominous development. There are some authorities who claim that our oil reserves will be used up in *less* than a century.

At the 1970 rate, we are burning about 400 gal of these fuels per year for every adult and child in the U. S. This quantity of fuel burned in internal combustion engines (based upon 1963 release estimates) releases about 150 lb of hydrocarbons, 800 lb of CO, and 45 lb of various oxides of nitrogen per year for every person in the U. S. [4]. Per automobile, this amounts to over a ton of pollution per year.

Admittedly, the new emission controls put on automobiles will reduce the pollutant rate per automobile per year drastically. The 1970 standards applied to all automobiles would reduce the emission to approximately one-third of the 1963 uncontrolled level. Certainly all of the autos on the road after 1970 will not measure up to these standards and the average total emission from each auto will be somewhere between the 1963 and 1970 levels.

If the consumption of auto fuels goes up as projected from Fig. 1, the future increased use will soon bring the total pollutant rate up to levels which are equivalent to or exceed the levels of the 1960s. It appears that reducing the emission rate per auto to the theoretical minimum will not permanently overcome the high pollution contribution by the internal combustion engine. In fact, it seems evident that more drastic measures will be necessary to cope with automobile-related pollution in the future.

Electric Power Consumption. The increased demand for electrical energy in the U. S. has averaged almost 7 percent per year during the 1960s [3]. The steady increase in the electrical power consumed is shown in Fig. 2. From this data it is anticipated that the U. S. will consume over 1500 billion kwh of electricity in 1970. By 1980, our demands probably will be doubled to reach 3000 billion kwh. If our consumption continues to double every decade, the electrical power consumption will reach a staggering value by 2000 A.D. of something like 10,000 billion kwh. One can only speculate how the power companies are going to provide such vast quantities of electrical energy. Expansion in generating capacity will come from three types of plants: (1) The fossil fuel burner (coal, gas, and oil); (2) the hydroelectric installation; and (3) the nuclear power plant. Despite a growing commitment to new nuclear plant construction, most of the initial increase will have to be assumed by the plants which burn fossil fuels. The hydroelectric plants are limited to places where natural conditions make it possible to tap a head of water. Generally these limited sites are far removed from populous industrial centers, so a greatly expanded

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[2] Numbers in brackets designate References at end of article.

hydroelectric capacity seems impossible—certainly in the U. S.

Currently, only 17 percent of the power developed in this country comes from hydraulic sources. Over 50 percent comes from coal burning, 23 percent from natural gas, and about 8 percent from fuel oil. The contribution from nuclear sources is negligibly small. There is a trend now toward conversion to gas or oil instead of coal as a fuel to overcome certain pollution difficulties.

The point is that the consumption of fossil fuels will go up at a tremendous rate if we try to respond to the greater demands for electrical power. This is the kernel of the problem. Can we in the U. S. meet the energy demands of the future without depleting fossil fuel reserves and spewing out vast quantities of pollutants?

Western Europe. Next to the North American continent, Western Europe is the largest consumer of energy in the world. As such it has a regional pollution problem because of intense industrialization. Fig. 3 shows the petroleum and coal consumption realized or estimated, from 1965 to 1980 [5]. The increase in petroleum consumption reflects both transportation and electrical energy demands. Although Europe has an ambitious program of developing nuclear power plants, fuel oil is being used at an increasing rate in place of coal. The substitution of oil for coal reduces pollution but aggravates the oil reserve problem. Coal is generally much more plentiful than oil in the world.

Means for Producing Energy

With some appreciation for the present and future demands for energy, let us look now at ways to generate it other than by the combustion of hydrocarbons.

Electrical Energy From Nuclear Fission. Currently, in the U. S., there is something like 70,000 MW of nuclear-electric power capacity under construction. It is estimated that by 1980 about 150,000 MW of capacity will be available. In Europe, it is anticipated that about 110,000 MW of nuclear-electric power will be ready by 1980 [6]. Despite this anticipated growth of nuclear-electric power in the U. S., it will still amount to only about 20 percent of the anticipated power needs in the 1980s.

The U. S. holds a key role in the development of nuclear-electric power over the entire world. First, the U. S. is the principal source of the enriched uranium used to charge the reactors. Second, we are the world's principal supplier of the reactor shells, heat exchangers, turbines, and electrical generation equipment. It is estimated that the U. S. capacity to produce enriched uranium must be doubled by the end of the '70s if the forecasted expansion of nuclear-electric power in the free world is to be achieved. Such an expansion in the near future requires immediate plans for adding capacity to existing uranium-enrichment plants.

There are some other developments in the wind that may affect the expansion of nuclear-electric power. One is the potential development of the fast breeder reactor which would drastically reduce the future need for enriched uranium. It is still too early to make any meaningful assessment of the success of such a reactor. At the present time, considerable research effort is being devoted to this type in both the U. S. and Europe. An

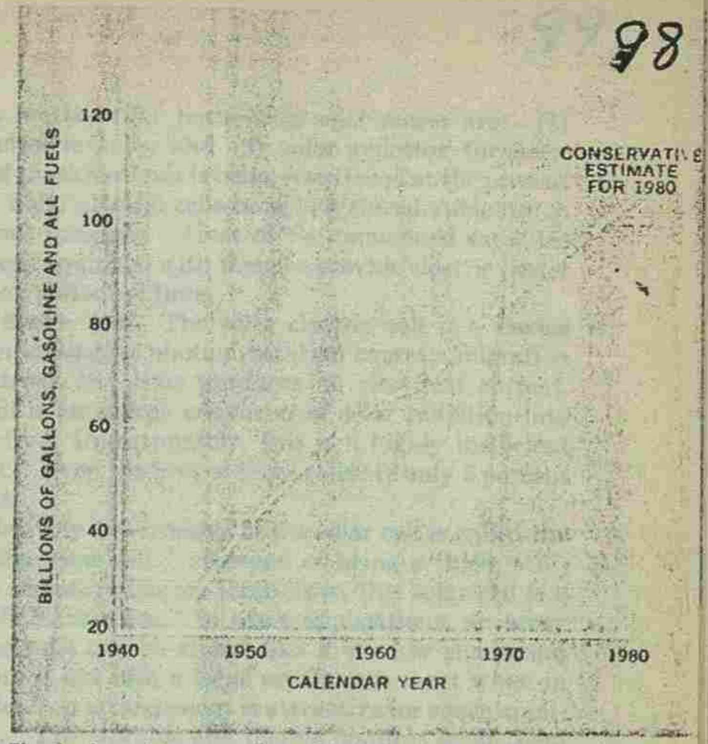


Fig. 1 Annual consumption of fuels for cars, trucks, and buses (from the Department of Transportation).

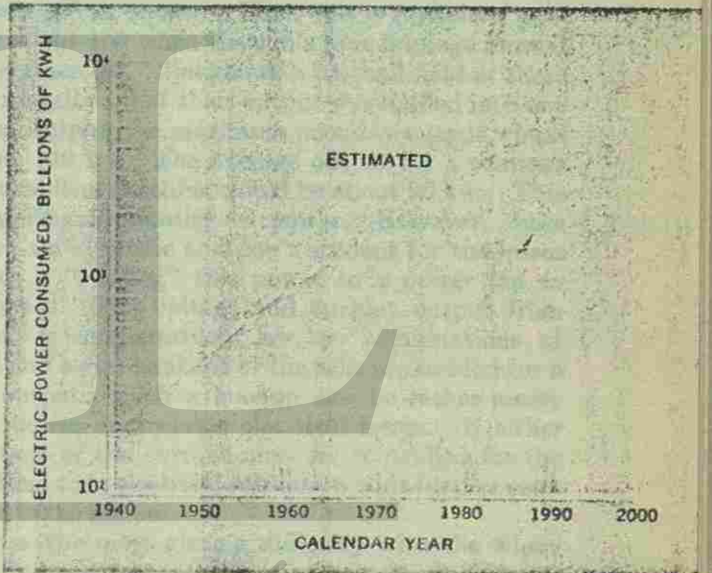
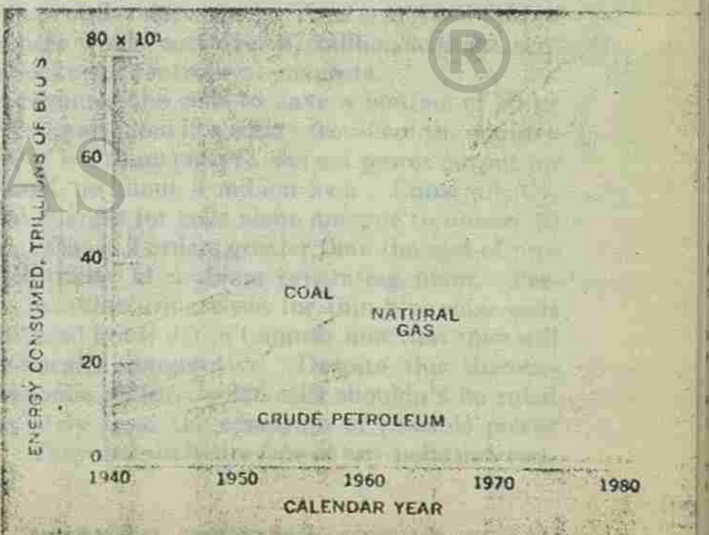


Fig. 2 Electrical power consumption in the United States.

Fig. 3 Consumption of energy in Western Europe according to fuel burned.



answer about engineering feasibility should be forthcoming by the mid '70s.

In the U. S., the pace of developments in nuclear-electric power has been retarded by legal barriers and by public fears, misunderstanding, and even hostility. The licensing requirements have been becoming more complicated despite improvements in design and performance of newer nuclear facilities. It does seem that the licensing procedure could be better codified and simplified. The current codes are complicated by ingrown precedents that need revision (and sometimes cancellation) to keep them current with new technology. The encumberances of a complicated licensing procedure have tended to raise costs excessively (along with the national inflation) and have discouraged private investment in the nuclear-electric power field. Public distrust and fear of nuclear-electric power plants must be overcome by better communication. Apparently a controlled reactor is still thought of as a bomb and this fixation makes it difficult to "sell" the public on the safety of the operation.

When it is more fully realized that reactors are safe and that they reduce air pollution, then perhaps they will become better accepted even near populated areas. Of course they aren't a panacea for the overall pollution problem. They are a potential source of thermal pollution. Because of lower operating efficiencies as compared to combustion plants (33 percent for a nuclear plant in contrast to 38 percent for a combustion plant), the nuclear-electric will contribute up to 10 percent more thermal pollution. Also, there is the problem of disposing of the expended radioactive fuel. As discussed in [7], there is the problem of environmental accumulation of tritium and krypton 85 in the waste-treatment process.

In the long-range view of future electrical power demands, it does seem mandatory that expansion of the nuclear-electric power capability be encouraged. Such a development would tend to conserve the world's fossil fuel reserves and would also alleviate atmospheric pollution in and around population centers. As was pointed out, thermal pollution and the disposal of radioactive waste are pollution problems peculiar to nuclear-electric power plants and these must be dealt with effectively.

The realization of a growing nuclear-electric capacity needs more than a continuing technological advance. Greatly needed is the moral support of the engineering community and a sound program of public relations. Misconceptions and superstitions about nuclear power must be displaced with accurate information that the average citizen can understand. The nuclear-electric power plant is a safe installation which does not contribute measurably to the radiation dosage which people are subject to everyday from such common things as building materials.

Solar Energy Conversion. When we are considering power sources we should not overlook the radiation from the sun. Almost 100 w of power per sq ft is transmitted to the earth surface by the sun. This power reaches our planet without any associated pollution. While we receive tremendous amounts of energy from the sun everyday, there aren't any really attractive ways of tapping this radiactive energy and distributing it.

Two methods for harnessing solar power are: (1) solar electric cells, and (2) solar reflector furnaces. Each of these methods is being researched at the present time. Solar electric cells have had considerable use in the space program. Most of the unmanned satellites have been equipped with them to provide electric power over long periods of time.

Solar Electric Cells. The solar electric cell is a device wherein impinging photon radiation causes a migration of electrons and thus produces an electrical current. The cell is an energy converter of solar radiation into electricity. Unfortunately, this is a highly inefficient process. Even the best of these cells are only 5 percent efficient.

A relatively new variety of the solar cell is called the "thin-film solar cell." Instead of being a thick, stiff-backed structure like its forerunner, this solar cell is a thin, pliable surface. In some applications, an array of these cells can be stored like a window shade and then pulled out into a large continuous sheet when in use. Such an arrangement is attractive for space applications. The storable and pliable features make them attractive for ground use also.

At present these thin-film cells are made in units approximately 3 in. square. Each unit is capable of generating about $\frac{1}{4}$ w when the sun's rays impinge normal to the surface [8]. Imagining a football field of these cells arranged so that their output was unified into one electrical output, the maximum noonday output would be about 140 kw. The average output for a summer day of cloudless sunshine would be about 90 kw. This is a significant quantity of power. However, these numbers are idealistic and don't account for the losses incurred in "bussing" this power to a power tap or switchboard. The voltage and current output from each cell is comparatively low, so combinations of parallel and series hookups of the cells are needed for a usable output. Such a hookup can be rather messy and introduce appreciable electrical losses. If either the voltage or the current must be controlled for the application, then electrical regulation adds further complexities to the system.

Perhaps the most glaring difficulty with the whole concept is an economic factor: namely, the initial cost of the thin-film solar cells. Their present cost is approximately $15 for the 3-sq-in. cell, or over $200 per sq ft. (It should be realized that they are in the research stage of development.) Thus a football field of these devices would cost over $7 million without considering hookup or control systems costs.

If one assumed the cells to have a lifetime of 20 yr and they were situated in a sunny section of the country (200 days of sunshine per yr), the net power output for 20 yr would be about 4 million kwh. Consequently, the initial charges for cells alone amount to almost $2 per kwh. This is 2 orders greater than the cost of producing electricity at a steam generating plant. Perhaps the manufacturing costs for thin-film solar cells will be reduced but it doesn't appear now that they will be economically competitive. Despite this discouraging economic picture, solar cells shouldn't be ruled out completely from the spectrum of possible power sources. They definitely are free of any pollution contribution.

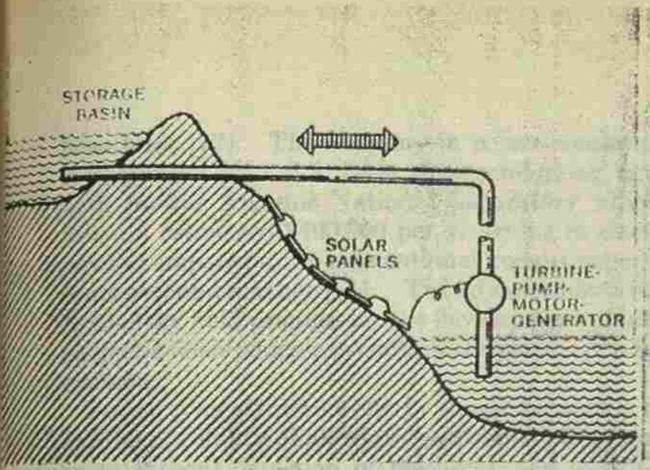


Fig. 4 Potential energy-storage system.

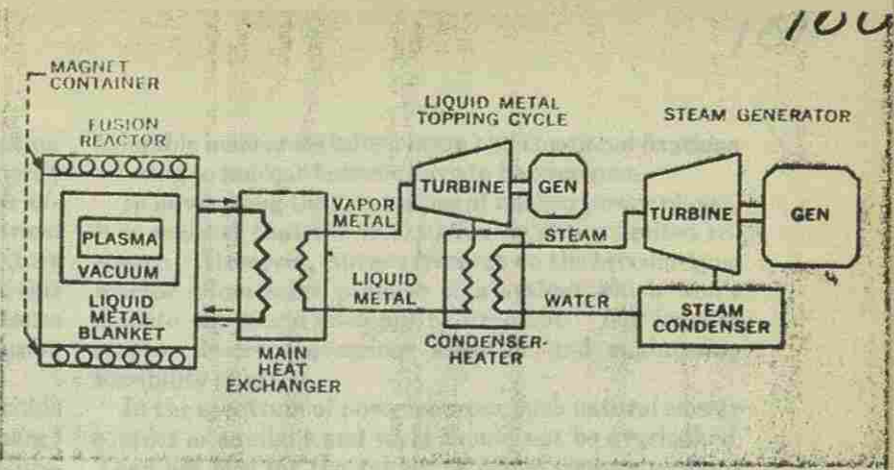


Fig. 5 A proposed topping-cycle fusion reactor powerplant.

Solar Furnaces. The solar furnace is an enlarged version of a trick that children in every modern generation have done. The idea is to concentrate the sun's rays by a lens or a mirror and focus them on some object to be heated or burned.

The largest solar furnace in existence is located in the little town of Mount Louis in the Pyrenees of France. As described in [9], the parabolic mirror is 140 ft high. It focuses on a furnace compartment where temperatures of 6300 F are achieved by concentrating about 1000 kw of solar energy. The parabolic mirror is fed by an array of 63 smaller mirrors which automatically track the sun during the day. This solar furnace is being utilized as a research tool in the synthesis of high-temperature, high-purity alloys.

Quite a few small countries are examining the possibilities of the solar furnace as a source of power because these particular countries are poor in fossil fuels and nuclear power sources.

In the U. S. one of the chief proponents of solar power is Professor E. A. Farber, Mem. ASME, of the University of Florida, Gainesville [10]. In his working laboratory, he has used solar energy for heating, pumping, cooling, and evaporating. He has demonstrated the applicability of solar energy to most of the types of thermal-cycle engines that have been run with combustion or nuclear energy sources. While Dr. Farber envisions greater application of solar energy systems he does not claim that solar energy can replace all other types of energy sources.

It is a nonpolluting source of energy and the energy is free for the taking without any depletion of the earth's fuel resources.

One major objection to solar energy is that it is only available when the sun is shining. There are energy-storage systems wherein electro-chemical, chemical conversion, or phase change or potential energy can be stored. These kinds of storage systems can be "charged" during the sunlight hours and the energy used on demand in the night hours.

As a simple example of a storage system, it has been suggested that energy could be stored potentially as a head of water. The head of water can be used to furnish hydroelectric power during the dark periods, Fig. 4.

Controlled Fusion. One of the far-out, futuristic means of generating power could be controlled fusion. Fusion is the process that goes on in active stars and in our sun—it is the prime source of all of our energy here on earth. Thus far, controlled fusion has not been achieved in the laboratory. However, over the past decade significant progress has been made in research which is aimed at achieving controlled fusion as a source [illegible] While not a reality as yet, many scientists and engineers are optimistic about actual achievement.

The realization of fusion in the laboratory entails the control and confinement of highly energetic nuclei of the isotopes of hydrogen and helium. Two of the possible reactions are deuterium–deuterium and deuterium–helium 3.

Kindling the fusion reaction requires high energies which are equivalent to temperatures in the millions of degrees. Temperature, as we normally think of it, is not a meaningful index of the energy of the particles engaged in the fusion reaction. It is better to talk about the energies in terms of electron volts. The fusion reaction takes place in the vicinity of 10,000 electron volts (10 kev).

There are two major problems which are obstacles to the realization of controlled fusion in the laboratory. The first is the confinement of the energetic plasma of the fusion reactants. The second is conservation or retention of some of the energy produced to sustain the ongoing fusion reaction at the high energy level. There is a question whether a net energy production will be realized.

Successful confinement of the plasma is probably the chief focus of current worldwide research effort in fusion. The effort is devoted to developing magnetic field "bottles" that will confine the plasma. Practically every magnetic geometry that has been conceived thus far has intolerable leaks that allow too much of the plasma to escape. Consequently, the confinement time for the particle reactants is too short and the fusion reaction does not go. As pointed out in [11], the residence time needed for the reaction is of the order of tenths of a second which is equivalent to millions of oscillations across the confinement volume.

The confinement of the fusion particles in a magnetic field requires the development of extremely powerful magnets. The superconductor magnet coil offers such a possibility. Many alloys exhibit superconducting qualities when they are subjected to very low cryogenic temperatures. At approximately 4 K (liquid helium environment) an alloy conductor may show practically no electrical resistance. Thus for an almost negligibly small expenditure of power, an extremely strong magnetic field can be developed. Magnets with field strengths up to 15 Teslas (150,000 gauss) have been built [12]. The economy in power consumption is illustrated by a 1.8 Tesla superconducting magnet built for the Argonne National Laboratory which effects an estimated $400,000 per yr saving in electrical power compared to a conventional room-temperature copper-wound magnet [11]. The advancements in this technology hold promise for the development of intense magnetic fields which can contain the plasma of a fusion reaction.

Fusion is an attractive energy source because it holds out the possibility of alleviating extremely large energy levels without depletion of resources, and even eliminating some of the pollutants produced by combustion or nuclear fission. For example there are no radioactive fission products to dispose of. However, there are environmental considerations such as neutron radiation and secondary radiation to be concerned about. The plant facility for housing the fusion reactor must be constructed to isolate and contain the dangerous radiation. Such shielding can be accomplished with current technology.

Courses of Action

In the areas of power production and transportation we are caught between the pincers of pollution and rapid depletion of oil reserves. Either one of these poses a threatening technological problem to a world which is growing in population at an alarming rate. Population trends and economic growth both portend greater demands for energy in the future.

There is no direct, easy answer to this dilemma. Many sociological and technological factors come into play in evaluating the problem and in suggesting courses of action to alleviate, or counteract, some of the issues. Now, as never before, the engineer who designs and operates power equipment and the engineer who designs transportation vehicles and systems must be fully conscious of their effects on the use of natural resources and on ecological and pollution disturbances. As long as engineering training has been in existence in this country, the engineering student has been instructed about his social responsibility and the effects of what he builds on society. Although these lessons probably have not been taken as seriously as they should, today, in crisis, they have momentous impact.

Electrical Energy. For electrical energy production, the coal-fired steam power plant appears to be the best bet for immediate expansion. Because of pollution considerations, steam power plants have been converting to oil or natural gas. Each of these fuels is in shorter supply as compared to coal. It would seem that better combustion systems and stack treatment systems could be developed that utilize coal with minimal pollution effects.

Largely because of a distrustful public, the thermal nuclear power plant has not been well accepted. Despite efforts by the industry and AEC, the safety regulations and licensing procedure have been in a state of flux which has made the designers and builders hesitant to promote new and larger plant designs. In the U.S., the amount of power produced by nuclear power plants is insignificant (less than 1 percent). There needs to be an intelligent information campaign directed to the general public about this type of equipment. Considerable inaccurate information and emotional fixations relating to nuclear hazards have to be overcome.

In advocating the greater use of nuclear power plants, it is realized that the nuclear fuel is also a limited resource. However, current research on the breeder-type reactor offers some promise of a system which won't deplete the world's supply of uranium. The breeder reactor deserves a serious scientific and engineering feasibility study.

In the spectrum of power sources, such natural energy sources as sunlight and wind should not be overlooked. They are free for the taking as prime sources without pollution difficulties. Transformation of their prime energies into a useful form requires considerable engineering ingenuity. It is recommended that such systems be given more serious attention by engineers.

It does seem obvious that growing demands for energy in the next century are going to require a breakthrough into a new means of producing that energy. The only entirely new possibility on the horizon is contained fusion. Certainly this concept offers the possibility of releasing large quantities of power from one installation. Power levels of the order 10^{10} w seem feasible. As mentioned earlier, contained fusion poses many overwhelming technological problems. But with sufficient incentive, these problems can be overcome. We ought to take on a major national effort in fusion power development.

Little has been done to develop major facilities for energy storage. Apparently it has seemed more feasible to build the system to accommodate fluctuations in load. The power-producing plant is designed to run continuously at some fraction of peak load. Auxiliary or standby units are often provided for emergency or abnormal load requirements.

However, recently it is evident that more and more breakdowns are occurring in electrical power distribution systems because they are being operated at near-capacity for long periods of time. Perhaps the series of events that lead to a catastrophic "brown out" could be obviated if some new short-duration energy-storage source were available. Storage of electrical energy in batteries or capacitors doesn't seem practical. One interesting energy-storage idea is being considered by NASA for the operation of large wind tunnels for short testing periods. It is to store high-pressure air within subterranean caverns. A head of water above the gas cavern would be used to maintain the high pressure.

Perhaps such a scheme could be used to get a sizeable gas turbine power-generation system on line within a comparatively short period of time during an emergency. In any event, it does appear that we could use energy-storage systems for existing energy-producing plants, and a more serious look at how to do this is a good engineering question.

Transportation. In our country we are accustomed to a freedom of movement which a privately owned automobile affords. However, the automobile population rate has been growing phenomenally in the last decade or so, and even getting rid of the discarded cars is a major national problem. Today, the auto is the greatest single contributor to atmospheric pollution and holds the major responsibility for the depletion rate of oil and other limited natural resources.

A revolutionary new design and marketing viewpoint for the automobile needs to be promulgated. The automobile ought to be looked upon as a transportation vehicle and not as an artifact of affluence or an "escape" machine. It is extravagant and wasteful to consider that a vehicle 18 ft long, 6 ft wide, weighing over 2 tons, and equipped with an engine delivering over 250 hp, is often used to transport only 1 person.

Besides the efforts to remove or reduce undesirable exhaust products, the new automobile needs to be greatly reduced in size and engine power. This can be done without sacrificing comfort or safety. Appreciable savings in total national fuel consumption would be realized if every manufacturer would reduce the horsepower and size of the new auto designs.

It is the whole engineering community's responsibility to support a major change in design philosophy and to inform the driving public about the consequences of indiscriminant use of the automobile. If the average driver could be made sensitive to an effort to cut out unnecessary auto travel, this too would aid in oil conservation and pollution abatement.

Beyond these recommendations are the efforts to find a cleaner substitute for the internal combustion engine. Thus far, the pressures to bring about a serious effort in this direction have not been too great. But this pressure is mounting and so some earnest developments may soon be in the making. For example, a short-range electric car would be suitable for commuting to work and for a great deal of the errand-chasing done in suburban communities.

Methods for mass transportation are receiving revitalized attention after a long period in which existing systems (primarily rail) have been allowed to decay and pass out of existence. In part, the neglect of mass transportation systems in and around urban areas has been due to a decentralization of commercial offices, plants, and stores from the heart of the city to highly dispersed locations in the suburban areas. Such dispersion has made it difficult for mass transportation to move people to their job locations.

In most major American cities, the population in the city proper has been going down. For example, in Detroit, Mich., the city population decreased an average of approximately 1 percent per yr during the 1960s while the suburban population increased at about 6 percent per yr. In metropolitan areas where new centralized transportation systems are being constructed, it is recognized that these will not cause a substantial dent in the commuter auto traffic in those areas. One of the most ambitious and costly new transportation systems is being built in San Francisco. It is estimated that when in operation, it could reduce auto traffic in the city by 2 percent [13].

One of the great challenges for the metropolitan transit system is to transport the city dwellers to jobs in the suburban areas. For this function, the flow of people is reversed from earlier concepts of mass transportation which were designed to take suburbanites into the city.

Rail systems linked with surface transportation could contribute to reductions in atmospheric pollutants and would help in the conservation of fossil fuels. The imaginative innovation of subway and surface mass transportation systems in populated areas should be one of the major engineering tasks of our time.

More and more, air transportation is carrying people who travel comparatively short distances (100 to 200 miles) as well as those who use the system for long-distance travel.

It is true that our airlines on domestic and overseas flights consume a sizeable portion of the nation's fuel (oil) consumption. The latest published figures (for 196) show that the airlines used about 8.5 percent of the national total. If one considers the amount of fuel consumed per mile, per passenger, the average jet plane when only half-occupied gets 14 passenger miles per gal. The average U. S. auto also gets about 14 miles per gal of fuel [3]. Thus, depending on the passenger loads in the auto and airplane, the fuel consumption per passenger mile in each can be about the same.

It may turn out that short-range aircraft are attractive transportation means for short trips between cities—especially in congested areas such as along the east coast. Short takeoff (STOL) and vertical takeoff aircraft may become important commuter transports of the future. They could reduce the use of the automobile as a commuter carrier.

Conclusion

At a time when mechanical engineers are taking a serious look at how they can continue contributing to the well-being of mankind, energy production and consumption is one of the major questions. Whatever steps are taken and whatever priorities are suggested by mechanical engineers, they must be responses to:

1 Ways to reduce the accelerating depletion of fossil fuels, primarily petroleum and natural gas.

2 New processes and restrictions for handling atmospheric pollutants.

3 Introduction of new means for energy production rather than combustion of fossil fuels.

4 Innovation of energy-storage systems of massive capacity.

5 Immediate revision of the design (and marketing) concepts for the automobile as a transportation medium.

6 The role of mass transportation in the conservation of energy and in reducing urban pollution as well as transporting people effectively.

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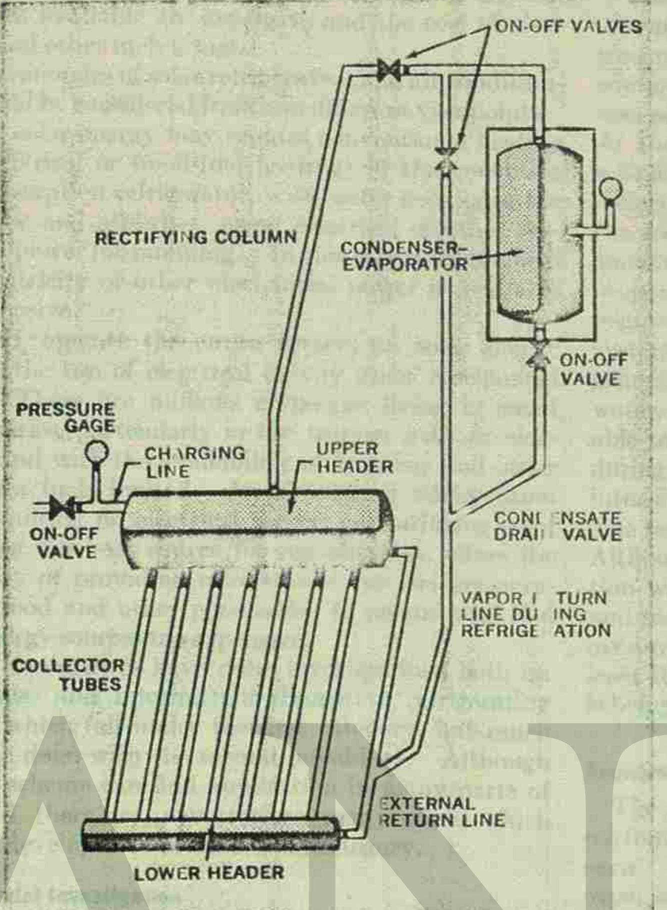

Fig. 1 Schematic representation of intermittent-absorption refrigeration system.

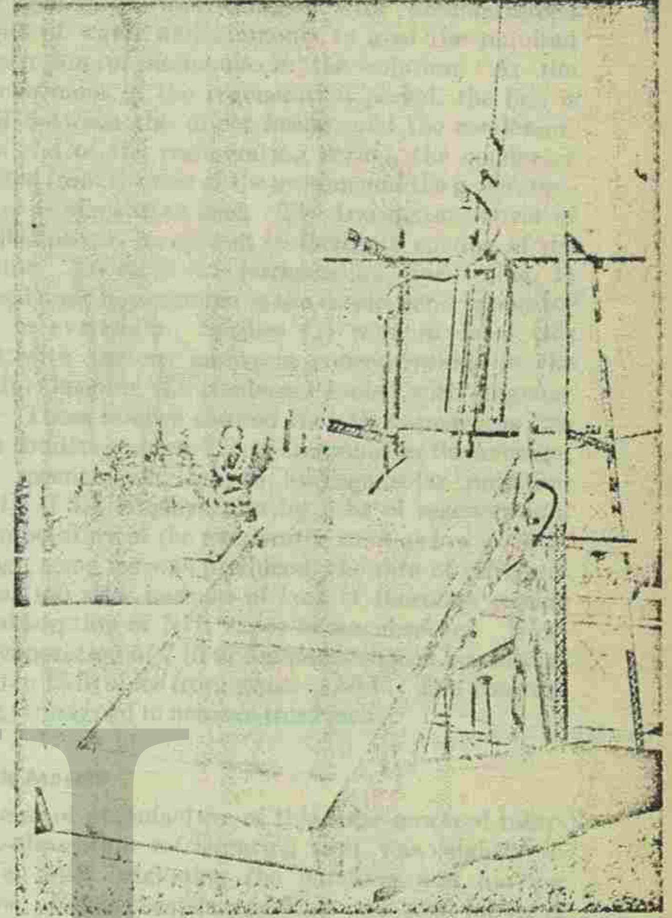

Fig. 2 Solar refrigeration apparatus uses flat-plate collector as the generator and absorber.

solar-powered refrigeration

ROBERT K. SWARTMAN[1] **and C. SWAMINATHAN**[2]

Solar refrigeration is attractive in parts of the world where electric power is not readily available and fossil fuels are expensive. Most work on solar refrigeration has been done on continuous-absorption refrigeration systems which cannot serve the purpose if the pumps require power. Furthermore, a continuous system becomes too complex to be handled by the local people. Here's a description, including the economic aspects, of a solar-powered intermittent-absorption refrigeration system that operates without electricity.

Of all the potential uses of solar energy, the most attractive is solar cooling. The possibility of providing a refrigerator or cooling unit to people living where conventional cooling units operated by electricity or fossil fuels are scarce or unavailable would be a tremendous boon to the world.

In tropical countries, there is great interest in solar

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Based on a paper contributed by the ASME Solar Energy Applications Group.

cooling because everyone desires cooling, but the devices now available are expensive and the cost of electricity and other fuels is high.

The economics of solar refrigeration and air conditioning should be considered from two different viewpoints.

First, solar energy may replace conventional heating (i.e., electrical or fossil-fuel heating) in the generator of an absorption refrigerator, with water cooling in the condenser and absorber, using electrical or other mechanical power for pumping. In this case, it is assumed that electricity or other mechanical power is available but expensive.

Second, operate the entire system on solar energy without the use of electrical or any other mechanical power. There are millions of people living in small communities, particularly in the tropics, without electricity, and with the availability of kerosene and other petroleum fuels limited. An absorption refrigeration cycle requiring no electrical power, and utilizing solar energy as the heat source for regeneration, offers the possibility of providing refrigeration for the preservation of food and other perishables to people who find other energy sources too expensive.

Many researchers have done investigations both on continuous- and intermittent-absorption refrigerating systems which fall under the first category, but much has to be done with the second possibility. Although the first scheme can find application in many parts of the world, there are, nevertheless, many places which need the development of the second category.

Experimental Investigation

Much of the work in solar cooling has been in continuous-absorption systems and less in intermittent-absorption refrigeration systems. Therefore, an intermittent-absorption refrigerating unit was designed, built, and tested [1].[3] A schematic diagram of the apparatus is shown in Fig. 1 and a photo of the system in Fig. 2.

This system used the flat-plate collector as the generator and absorber. The collector–generator apparatus consisted of $\frac{1}{2}$-in. steel pipes connecting a 2-in. feeder and 6-in. header. Thin copper sheets were soldered to the tubes and the whole collector–generator apparatus enclosed in an insulated wooden box. The collector was covered with a transparent double glazing with an area of about 18 sq ft. This system was tested with an ammonia–water solution at different concentrations. The pressure in the system is controlled by the condensing temperature. In the tropics, the daytime temperature is usually high during summer, which increases the pressure of the system to a high level when the condenser is air cooled. The difficulty of high pressure can be obviated by using an ammonia–sodium–thiocyanate combination instead of ammonia–water. Usually, ground water is much cooler than the ambient temperature. Well water could be used as a bath for condensing the ammonia vapor at a much reduced pressure. This, in turn, would increase the quantity of ammonia condensed for useful refrigeration. Hence, cooling the condenser with stagnant water, and the absorber with ambient air, is an ideal combination for locations having high daytime temperatures.

The generator was charged with predetermined amounts of water and ammonia to give the required concentration of ammonia in the solution. At the commencement of the regeneration period, the line is opened between the upper header and the condenser. At the end of the regeneration period, the condenser is isolated from the rest of the system and the generator–collector is allowed to cool. The transparent cover of the collector can be opened to facilitate cooling of the generator. To carry out refrigeration, line 7 (Fig. 1) is opened and the ammonia in the condenser–evaporator begins to evaporate. Studies [2] were made of this system with various ammonia concentrations in the generator, keeping the condenser cooled with stagnant water. These studies showed that this apparatus was able to condense about 7 lb of ammonia on the average, during regeneration, for an average solar radiation intensity of 1.1 langleys/min for 6 hr of regeneration. The temperature of the evaporator went as low as 10 F. Although some ice was produced, the rate of refrigeration was too slow because of lack of thorough mixing and reabsorption of NH_3 vapor in the absorber. However, evaporation of 7 lb of ammonia should produce at least 10 to 15 lb of ice from water at 80 F. The absorber is being redesigned to achieve this result.

Economic Aspects

The cost of manufacture of this solar-powered intermittent-absorption refrigerating unit was slightly in excess of $400, excluding the handling and moving expenses. Using cheaper materials and local labor, it should be possible to reduce this cost. The annual depreciation and maintenance of the unit, assuming 10 percent of the initial cost, is thus of the order of $40. The annual output of ice would be in the range of 3600 lb, assuming 12 lb of ice per day for 300 days of sunshine or 3000 lb of ice for 250 days of sunshine. Since this system utilizing no electrical or other energy than solar is intended for places where there is abundant sunshine, it is reasonable to assume that sunshine would be available for more than 250 days per year. Therefore, the the cost of ice would be of the order of 1.3 cents per lb.

Ice at this price would be a boon to people living in areas where electricity and other conventional energy sources either are not available or are expensive. Comparing this cost to the usual cost of ice in the range of 2 to 4 cents per lb in tropical countries such as India, intermittent solar refrigeration is attractive. The cost of ice from solar-powered intermittent-absorption refrigeration greatly depends on the cost of the generator–absorber and condenser–evaporator units. Since the generator and absorber are combined with the flat-plate collector in the system investigated by the authors, the cost of ice produced by this unit would be reduced by a reduction in the overall cost of the unit.

Using indigenous materials and local labor in India, one of the authors designed and built a flat-plate collector, covered with two layers of glass, for a solar air conditioner [3], at $2.50 (18 rupees) per sq ft. This cost would be quite reasonable in most tropical countries. Therefore, ice could be produced at low cost by a solar-powered intermittent-absorption system like the one tested by the authors, provided several major problems associated with the system could be overcome.

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[3] Numbers in brackets designate References at end of article.

TABLE 1. Comparative Costs of Refrigeration

Vapor Compression Refrigeration

Assume capital cost of $180.00 for 10-cu-ft cabinet, ⅛-hp motor, COP = 4, efficiency of motor = 0.8, and cooling load = 7450 Btu/day

Energy Source	Energy Cost	Capital Charges	Operating Charges	Cost of Ice
electricity	3¢/kwh	5¢/day	4.2¢/day	0.25¢/lb
electricity	5¢/kwh	5¢/day	7.0¢/day	0.32¢/lb

Absorption Refrigeration

Assume capital cost of $700.00 for NH_3—H_2O unit, 9-cu-ft cabinet, COP = 0.5, efficiency of heating value to generator = 0.7, cooling load = 6000 Btu/day

Energy Source	Energy Cost	Capital Charges	Operating Charges	Cost of Ice
natural gas	$1.05/$10^6$ cu ft	19¢/day	2.52¢/day	0.72¢/lb
kerosene	20¢/U.S. gal	19¢/day	2.32¢/day	0.71¢/lb
kerosene (in India)	35¢/U.S. gal	19¢/day	4.08¢/day	0.77¢/lb
propane	$10.00/100 lb	19¢/day	8.64¢/day	0.92¢/lb
electricity	3¢/kwh	19¢/day	15.00¢/day	1.13¢/lb
electricity (in India and Burma)	5¢/kwh	19¢/day	25.00¢/day	1.46¢/lb

Solar-Powered Absorption Refrigeration

Unit	Capital Cost	Capacity of Ice Production	Capital Charges and maintenance	Cost of Ice
UWO (NH_3—H_2O)	$400.00	3000 lb/year	$40.00/year	1.33¢/lb
Farber		41 lb/day		not known
Chung & Duffie				$4.00/ton
Trombe & Föex				0.9-1.4¢/lb

Note: Assume amortization of 10% of capital cost per annum; cooling required to freeze water from 85 F to ice at 30 F is 200 Btu/lb; for commercial absorption and vapor compression units, use factor is 40% and losses are 40%.

The major problem is the performance of the flat-plate collector as an efficient absorber. The flat-plate collector as a heat dissipator is an area where nothing has been done so far. Plans are underway to investigate this area and to design an efficient absorber suitable for intermittent-absorption refrigeration.

Little information is available on the exact cost and economics of solar refrigeration. Chung and Duffie [4] estimated that an intermittent-absorption food cooler having a capacity of 1000 Btu/cycle would cost $50, a continuous-absorption ice machine $300, and $150 for a solar heat exchanger, so the cost of ice production would be of the order of $4.00 per ton. Trombe and Föex [5] estimated the cost of ice per kilogram to be of the order of 7 to 10.5 old francs (0.9 to 1.4 cents per lb) by solar refrigeration. Tabor [6] has derived the economics of solar refrigerators from thermodynamic considerations and concludes that solar refrigerating systems with storage facilities will not compete with kerosene-operated units unless the local price is several times the "fair" price of $60 per ton (19 cents per U. S. gal). These figures might not be accurate today because of the increase in the cost of materials and labor. However, the paper by Ba Hli et al. [7] suggests that ice at 1 cent per lb from a unit producing 50 lb per day should cost not more than $500. The recent investigation by Farber [8] on a compact solar refrigerating system seems to be encouraging, although the cost analysis of ice production in this system is not available.

The approximate costs for various systems proposed by different investigators are summarized in Table 1.

Conclusion

Indications are that a solar-powered intermittent-absorption refrigeration system has an important role. It can compete favorably with conventional systems and, in fact, can be superior in many parts of the world.

Acknowledgment

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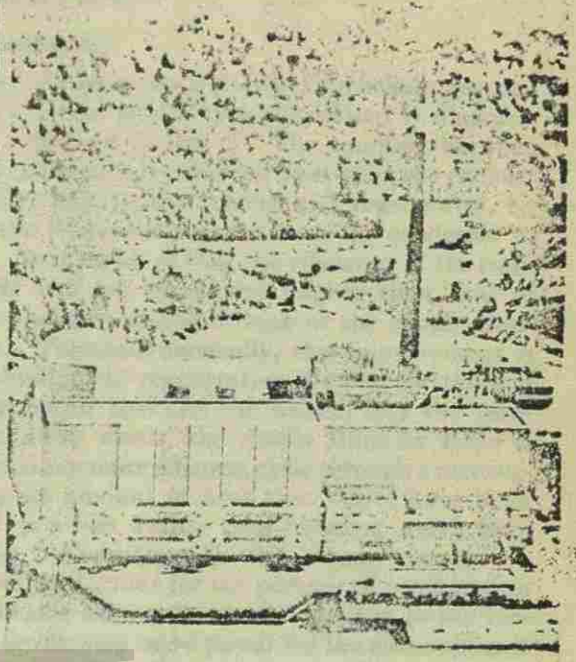
combined helium and steam cycle for NUCLEAR POWER PLANTS



Here's how a closed-cycle helium gas turbine can be combined with a Rankine steam cycle to achieve an appreciable improvement in thermal efficiency. Thermal energy in the hot gases from the regenerator of the helium cycle heats the feedwater in the Rankine cycle. Although the study includes different arrangements of the gas cycle using combinations of intercooling and reheating, the most favorable results are obtained with a simple gas cycle.

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THE IDEA of using closed-cycle gas turbines in connection with gas-cooled nuclear reactors was introduced as early as 1946 [1].[3] Rapid development in the gas turbine during the late forties and early fifties, using both the open- and closed-cycle concepts, brought it up to a competitive level with the steam turbine. During the last ten years or more, closed-cycle gas turbines using air as a working medium have been operating successfully. With a parallel and equally successful effort in the development of high-temperature gas-cooled nuclear reactors, direct coupling of helium-cooled reactors to closed-cycle gas turbines proved to be of great advantage. Gas-turbine cycles with one or two intercooling stages together with one reheating stage have been studied in detail for plant sizes up to 1000 MWe. For very large sizes of power plants (2000 MWe and more), the idea of combining the helium-gas-turbine cycle with a steam power cycle has now become more realistic.

Such a combination is thermodynamically advantageous and yields an overall thermal efficiency higher than that of either the steam or gas cycle operating separately. The improvement in the combined thermal efficiency is mainly achieved through a total or partial utilization of the waste heat from the gas cycle into a steam cycle.

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This article is based on a paper contributed by the ASME Nuclear Engineering Division.

[3] Numbers in brackets designate References at end of article.

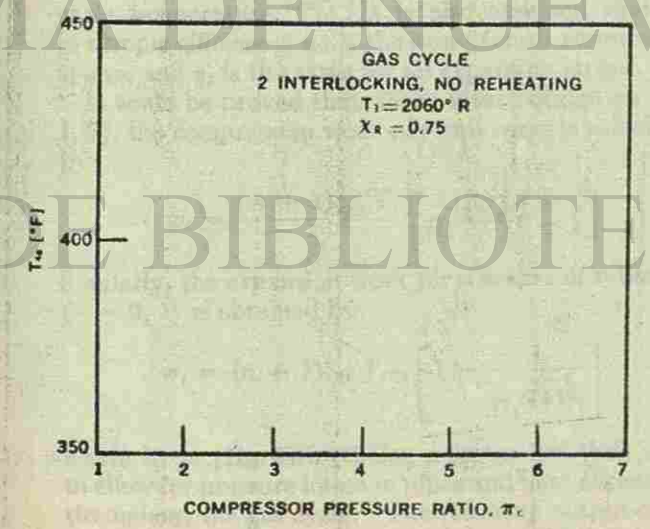
There are different possibilities for such a combination:

- Non-regenerative simple gas cycle where the waste heat in the exhaust gases is used to generate the steam necessary for the Rankine cycle. In this case, only the high-temperature part of the exhaust-gas energy could be used, while the low-temperature part is considered as a loss.
- The same cycle combination as suggested above but where the low-temperature heat is led back to the gas cycle to be partially utilized in regeneration of compressed gases [2]. An amount of low-temperature thermal energy still will be lost because the gas temperature after the compressor is relatively high.
- A combined gas-steam cycle with or without intercooling and reheating in the gas cycle, where the high-temperature exhaust energy is used for regeneration in the gas cycle. The remaining energy in the gases could be used for heating the feedwater in the steam cycle.

This last possibility provides a nearly complete utilization of the waste heat from the gas cycle and, therefore, is an interesting case for study. The purpose of this article is to analyze this possibility and explore different combination potentials.

The curve in Fig. 1 shows an example of the exit temperature from a closed-cycle helium gas turbine with two intercoolings and one reheating and using a regenerator of 0.75 effectiveness [3]. The temperature of the helium gases leaving the turbine varies between about 440 F at a compressor pressure ratio of 1.5 to nearly 370 F at a pressure ratio of 6; even higher temperatures are expected if no intercooling is used. These gases have to be cooled down to 60 to 80 F before entering the compressor again. The amount of thermal energy rejected in this case represents a waste that could be utilized in combined cycles. This thermal energy, being at a relatively low temperature, cannot be used for steam generation with the quality required to operate a power plant. However, it could be used for feedwater heating. Another advantage in the case of using helium is its relatively high specific heat and thermal conductivity, which makes it a very favorable fluid for heat-exchanger design.

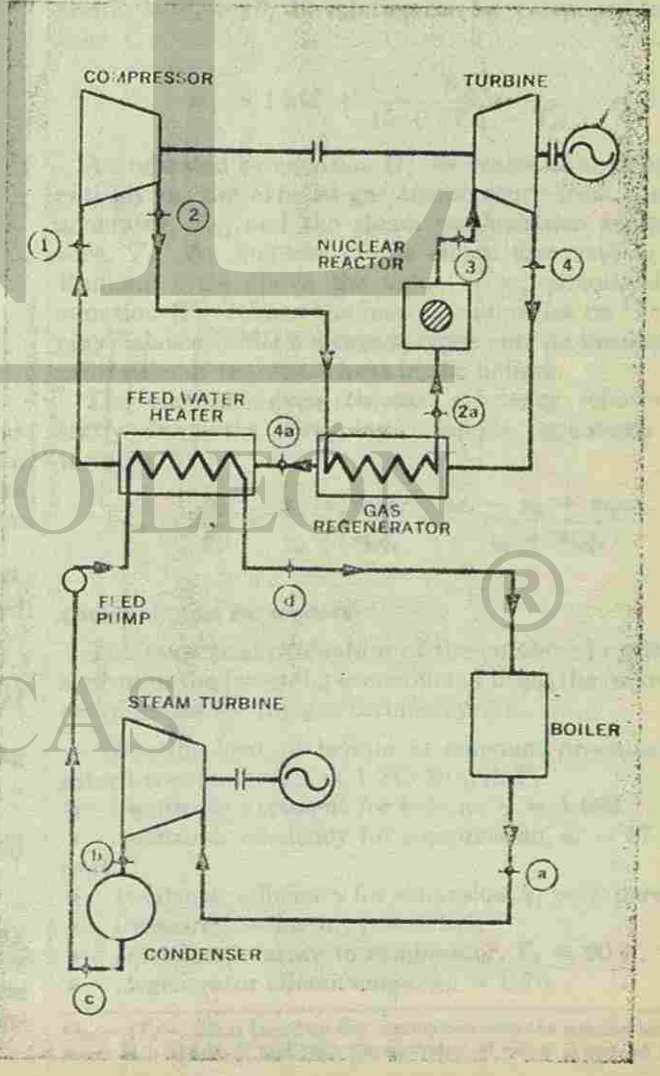
Fig. 1 Helium gas temperature at exit from the regenerator.



The Combined Cycle

The idea of combining a closed-cycle helium gas turbine with a steam power cycle (Rankine) is diagrammatically explained in Fig. 2. The coupling between the two cycles is mainly achieved by cooling the exhaust helium, after leaving the turbine and regenerator, by means of the feedwater pumped from the condenser to the boiler. As a result of this, the efficiency of the combined cycle will be, in general, higher than that of either the closed-cycle gas turbine or the simple Rankine cycle. Thermodynamically, this improvement is achieved through the regenerative effect of the thermal energy exchanged between the helium and the feedwater. In other words, the simple Rankine cycle is transferred into a more efficient cycle through a regeneration using an amount of heat that would have been considered as a loss, rather than bleeding steam from the turbine. Consequently, the steam usually extracted from the turbine for the purpose of regeneration in the feedwater heaters is saved to expand in the turbine, thus developing more power for the same amount of heat added in the boiler.

Fig. 2 Combined-cycle arrangement.



In this analysis, a simple non-reheating Rankine cycle is combined with different arrangements of the gas cycle. The general layout of the cycle is shown in Fig. 2, while Fig. 3 represents a combined temperature–entropy diagram. Although the representation in both Figs. 2 and 3 is made for a simple gas cycle, it should be kept in mind that:

- The compression in the gas cycle could be performed with none, one, or two intercooling processes.
- The expansion in the gas cycle could be either straight or with one reheating.
- The feedwater heater in the steam cycle is only diagrammatically symbolized in Fig. 2; in fact, there could be more than a single heater in series.

The thermodynamic analysis of the gas turbine is further simplified by assuming complete and ideal intercooling to the compressor inlet temperature, T_1, as well as complete and ideal reheating to the maximum cycle temperature, T_3. It is also assumed that the isentropic efficiency, η_c, is the same for all compression stages, and η_t is the same for all expansion stages.

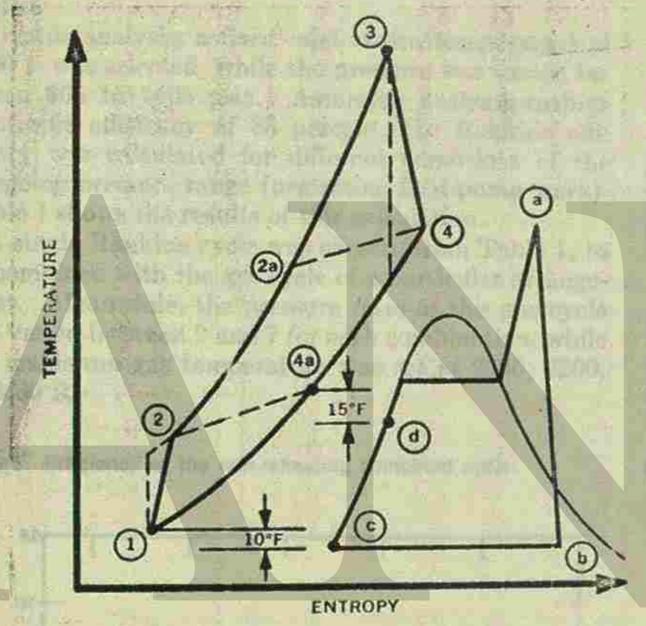


Fig. 3 Temperature–entropy diagram of the combined cycles.

It could be proved that, for m intercoolings ($m = 0, 1, 2$), the compression work per unit mass is calculated by

$$w_c = \frac{(m+1)c_{p_{He}}T_1}{\eta_c}\left[\Pi_c^{\frac{\gamma-1}{(m+1)\gamma}} - 1\right] \qquad (1)$$

Similarly, the expansion work for n stages of reheating ($n = 0, 1$) is obtained by

$$w_t = (n+1)c_{p_{He}}T_3\eta_t\left[1 - \frac{1}{\Pi_t^{\frac{\gamma-1}{(n+1)\gamma}}}\right] \qquad (2)$$

where $\Pi_t = \zeta\Pi_c$, with ζ being a factor less than unity to allow for pressure losses in pipes and heat exchangers throughout the gas cycle. The resulting output of the gas cycle per unit mass flow of helium could thus be obtained by

$$w_g = w_t - w_c \qquad (3)$$

while the corresponding heat added is calculated by

$$q_g = c_{p_{He}}[(n+1)T_3 - T_{2a} - nT_4] \qquad (4)$$

The calculation of the power developed by the Rankine cycle is obtained with the help of a Mollier chart. Neglecting the feed-pump work and referring to Fig. 3, the net output of the Rankine cycle per unit mass flow of steam is given by

$$w_s = (h_a - h_b) \qquad (5)$$

whereas the heat added in the boiler is calculated by

$$q_s = (h_a - h_d) = [h_a - (T_d - 32)] \qquad (6)^4$$

In examining Fig. 2, it can be seen that the hot helium leaving the regenerator is used in a counterflow heat exchanger to heat the feedwater. It is assumed here that the temperature difference between helium and water is about 15 F at the hot end and 10 F at the cold end of the heat exchanger. An energy balance shows that in order to satisfy this condition, m_s pounds of steam (feedwater) have to be used for each pound of helium such that

$$c_{p_{He}}(T_{4a} - T_1) = m_s c_{p_{H_2O}}(T_d - T_c)$$

Given $c_{p_{He}} = 1.242$ Btu/lb-F and considering that according to the foregoing assumption, $T_{4a} = T_d + 15$ and $T_1 = T_c + 10$, the relation can be rearranged to obtain

$$m_s = 1.242 + \frac{5.21}{15 + (T_{4a} - T_c)} \qquad (7)$$

As indicated by equation (7), the value of m_s depends entirely on the exhaust-gas temperature from the regenerator, T_{4a}, and the steam condensation temperature, T_c. An increase of the steam flow rate in the Rankine cycle above the value of m_s calculated by equation (7) violates the basic assumptions on the energy balance, while a decrease represents an incomplete utilization of the waste heat in the helium.

The combined-cycle thermal efficiency follows directly from the foregoing relations, equations (1) through (7)

$$\eta_{th} = \frac{w_T}{q_T} = \frac{w_g + m_s w_s}{q_g + m_s q_s} = \frac{w_t - w_c + m_s w_s}{q_g + m_s q_s} \qquad (8)$$

Choice of Cycle Parameters

The numerical evaluation of the combined cycle described in the foregoing is conducted using the following assumptions for the gas-turbine cycle:

- Specific heat of helium at constant pressure (assumed constant), $c_{p_{He}} = 1.242$ Btu/lb-F.
- Isentropic exponent for helium, $\gamma = 1.662$.
- Isentropic efficiency for compression, $\eta_c = 87$ percent.
- Isentropic efficiency for expansion, $\eta_t = 89$ percent.
- Pressure loss factor, $\zeta = 0.935$.
- Inlet temperature to compressor, $T_1 = 90$ F.
- Regenerator effectiveness, $\chi_R = 0.75$.

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[4] $h_d = (T_d - 32)$ is based on the assumption that the specific heat for water is 1 Btu/lb-F and that the enthalpy of water is zero at 32 F.

In choosing the appropriate steam cycle for use in combination with the helium gas cycle, the following should be considered: The condenser pressure of the Rankine cycle should be chosen as low as possible for favorable operation of the Rankine cycle while at the same time matching the inlet temperature to the compressor of the gas cycle. The 10 F temperature difference previously assumed between the cold helium and water condensate would result in a condenser temperature of 80 F. The corresponding vapor pressure of water is about 1 in. Hg, which determines the condenser pressure. On the other hand, the inlet pressure and temperature to the steam turbine may be changed. These changes are basically intended to examine the effect of varying the Rankine-cycle efficiency on the performance of the combined cycle. In an attempt to reduce the amount of calculation without endangering the generality of the results, only one parameter is varied.

In this analysis, a fixed inlet steam temperature of 1000 F was selected, while the pressure was varied between 865 to 1465 psia. Assuming a steam-turbine isentropic efficiency of 85 percent, the Rankine efficiency was calculated for different conditions of the foregoing pressure range (neglecting feed-pump work). Table 1 shows the results of this calculation.

A single Rankine cycle was chosen, from Table 1, to be combined with the gas cycle of a particular arrangement. Meanwhile, the pressure ratio of this gas cycle was varied between 2 and 7 for each combination, while the maximum gas temperature was set at 2060, 2260, or 2460 R.

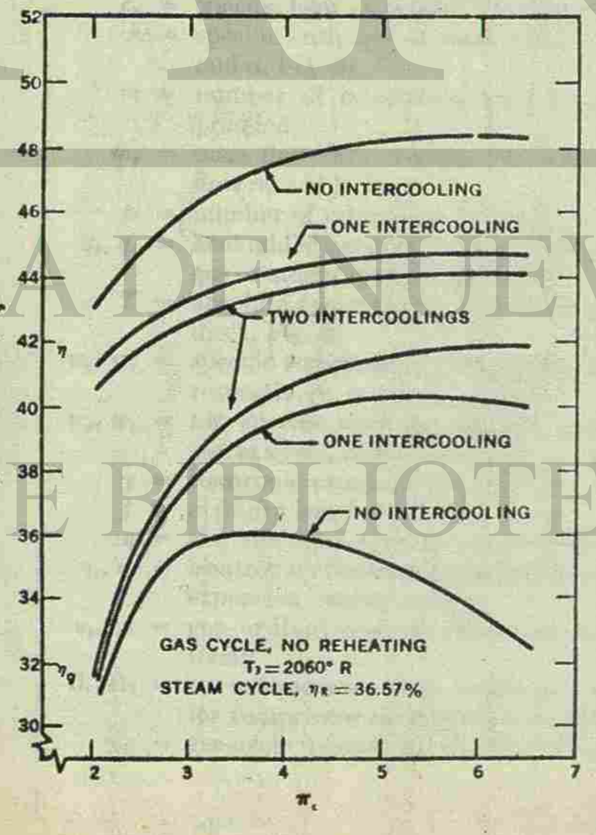

Fig. 4 Efficiency of the non-reheating combined cycle.

Analysis of Results

Selecting a representative sample of the results obtained, it is possible to demonstrate the improvement in the thermal efficiency of the combined cycle. For this purpose, one can consider the different arrangements obtained by combining one of the Rankine cycles in Table 1 with a gas cycle operating with different parameters. By choosing cycle number 2 in the table (operating with superheated steam at 1000 F and 1065 psia at a condenser pressure of 1 in. Hg), the resulting Rankine thermal efficiency is 36.57 percent. This cycle is combined with two main gas-cycle arrangements:

Non-reheating helium gas cycle
2 Single reheating helium gas cycle.

In both arrangements, none, one, or two intercoolings were used as an additional parameter. The results obtained are plotted in Figs. 4 and 5 for the whole range of

TABLE 1

Cycle	Inlet Pressure	Rankine Efficiency %
1	865	35.94
2	1065	36.57
3	1265	37.1
4	1465	37.58

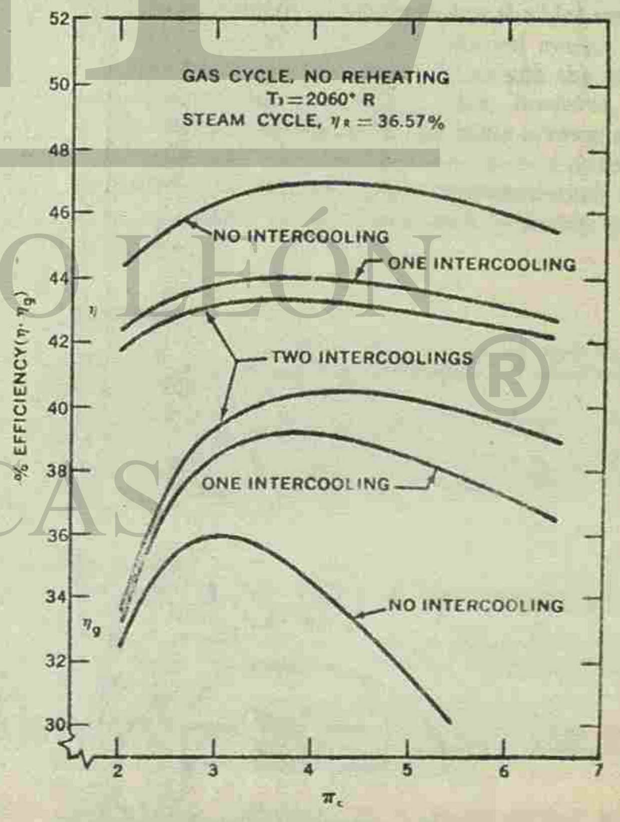

Fig. 5 Efficiency of the combined cycle with one reheating.

variation in the compressor pressure ratio. Both the gas-cycle thermal efficiency, η_g, and the combined-cycle thermal efficiency, η, are represented. The maximum gas-cycle temperature in both arrangements was selected to be 2060 R. Fig. 4 shows the results for the non-reheating arrangement, while Fig. 5 includes the results for single reheating. From these plots the following is evident:

- The thermal efficiency, η, is improved appreciably over the individual cycle efficiencies through the utilization of the thermal energy in the exhaust helium leaving the regenerator to heat the feedwater on the Rankine cycle.
- The efficiency improvement is higher in the case of no intercooling than either for one or two intercooling stages because the thermal energy in the exhaust gases decreases as the number of intercoolings increases. For example, the thermal efficiency of a non-reheating combined cycle (Fig. 4) at a compressor pressure ratio of 3 has increased from 36 to 46.5 percent without intercooling, while when using one intercooling the efficiency increases only from 38.5 to 43.8 percent. Even less improvement is obtained when two intercoolings are used.
- **The compressor pressure ratio for maximum efficiency changes to a higher value through the use of the combined cycle. The shift is smaller in the case of non-reheating (Fig. 4) than with one reheating (Fig. 5), and it decreases upon increasing the number of intercoolings.**

Nomenclature

c_p = specific heat at constant pressure
h = specific enthalpy of steam (index a, b, and d, Fig. 3)
m = number of intercoolings during compression
m_s = mass flow rate of steam per unit mass flow rate of helium
n = number of reheatings during expansion
q_g, q_s = heat added per unit mass flow rate in the gas or steam cycle, respectively
T = absolute temperature (for different indices, Fig. 3)
w_c, w_t = specific compression or expansion work, respectively, in the gas cycle
w_g, w_s = net specific work for the gas cycle or steam cycle, respectively
γ = isentropic exponent for helium
ζ = pressure loss factor
η = the combined-cycle thermal efficiency
η_c, η_t = isentropic efficiency for compression or expansion, respectively
η_g, η_R = gas- or Rankine-cycle efficiency, respectively
Π_c, Π_t = overall pressure ratio in the gas cycle for compressor or turbine, respectively
χ_R = gas-cycle regenerator effectiveness

After examining these results it can be concluded that the highest improvement in the combined-cycle efficiency is obtained with the simplest gas cycle. A combined thermal efficiency of about 47 percent is achieved with a simple gas cycle (no intercooling and no reheating) at a moderate compressor pressure ratio of about 3.5. At the same pressure ratio, when using one reheating, the combined-cycle efficiency is about 49 percent. The latter, however, could be raised to about 50 percent by increasing the compressor pressure ratio to about 6. Although this is a higher thermal efficiency, it is accompanied by two main disadvantages. First, a helium turbomachine designed to operate at a pressure ratio of 6 has a relatively large number of stages, which may cause design difficulties. Second, reheating the helium within a nuclear reactor is difficult and rather complicated.

An investigation into the effect of other operating parameters on the combined-cycle efficiency, limiting the study to the simple gas cycle as being the most favorable, shows that the combined efficiency increases linearly with increasing Rankine-cycle efficiency. On the other hand, an increase of about 100 F in the maximum gas-cycle temperature produces an average improvement of one point in the combined-cycle efficiency.

Summary

An improvement of the combined thermal efficiency is achieved above the thermal efficiency of either the gas or Rankine cycle. The most favorable combination is found to be between a simple gas cycle with no intercooling or reheating and a simple Rankine cycle. The efficiency improvement under these conditions amounts to about 10 points at a compressor pressure ratio of 3.5. This does not represent the highest possible efficiency obtained with the combined cycle. Greater improvement could be achieved through the use of one reheating in the gas cycle. This, however, is connected with complication in the cycle arrangement.

It is believed that, for very large power outputs (i.e., 2000 MWe and above), such a combined-cycle arrangement represents a successful and probably economic solution.

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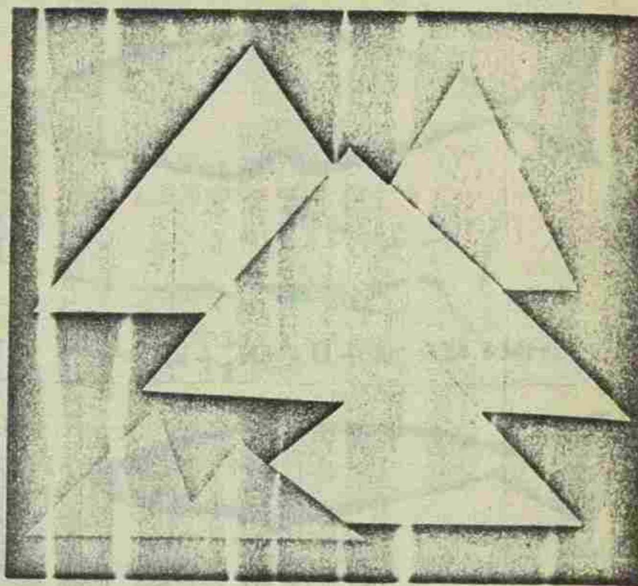
POWER IN THE YEAR 2001



Part 1—Dawn of the Solar Age

Those bounties of nature, our fossil fuels, will be effectively exhausted in 200 or so years. Before this comes to pass, we shall burn the seas and the rocks or, ultimately, directly tap the sun's heat for our energy needs. This is not a statement of desperation. Technologically, no insuperable problems exist. The core problem is rather one of bias and inertia that seems not to evaporate except under the heat of crisis. To place the energy picture of the not-too-distant future into focus, a series is initiated, in this issue, of major and innovative energy systems that have this in common. Any one of them, if fully exploited, could meet our energy needs for many millennia with minimal or no insult to the environment.

SAMUEL WALTERS[1]

"ENERGY," said James Clerk Maxwell, nineteenth-century British scientist, "is the go of things." And ever since Watt's engine in the eighteenth century used the chemical energy of wood and coal to power industrial machines, we have been "going" at an accelerated rate. Prior to this, for millennial time, man plodded along, energy-wise, at a donkey walk. But between 1830 and 1860, we broke into a trot. Reaction and impulse turbines for extracting the potential energy of water stored at high heads were developed. On the heels of these developments came Otto, Daimler and Diesel. Their achievements, between 1874 and 1905, led to practical internal-combustion engines operating on liquid hydrocarbon fuels such as oil, gasoline and kerosene. At about the same time, Parsons developed the steam turbine and not long after that at about the beginning of the twentieth century, the first steam-turbine-driven electric power generating plants went into operation. We broke into a canter.

Per capita energy consumption and population soared—together. Until recent times they have always moved together. In fact, curves of population and per capita energy consumption over the past score of millennia are indistinguishable from one another. They plot as a nearly horizontal line just above zero for the entire period of human history until the last thousand years or so. Then a barely perceptible rise begins as the present is approached. Here the curve turns abruptly upward in a nearly vertical rise toward the 1970 world population figure of about 3.6 billions. Curves of energy production from the fossil fuels behave similarly except that in the very recent past they begin at zero [1].[2]

We are probably now approaching full gallop. In terms of *Q* units of energy,[3] the energy transformation is startling. From the time of Christ until the middle of the last century mankind used about 8 *Q*. In the last century 4 *Q* were consumed, and, extrapolating from current trends, the need in the next century will be between 100 and 400 *Q*. (The United States alone, with only 6 percent of the world's population, consumes 37 percent of the world's energy.) Even if all known marginal and submarginal resources are considered, the problem of diversifying the energy source would not be alleviated. These resources are limited—about 81 *Q* for the United States and 453 *Q* for the entire planet [2].

Since the known recoverable reserves of fossil fuels are limited (6 *Q* for the United States and 23 *Q* for the entire world) and the supply of uranium 235 will be in short supply within 20 years, the human population

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[1] Staff Editor, MECHANICAL ENGINEERING.

[2] Numbers in brackets designate References at end of article.

[3] 1 *Q* = 10^{18} Btu or 2.93 × 10^{14} kwh. Recall that the British thermal unit, or Btu, is defined as the heat necessary to raise by 1 deg F the temperature of 1 lb of water. To give a physical idea of the size of the *Q* it represents the heat liberated by the combustion of 38 billion tons of bituminous coal. Another example: If we had 400 million automobiles, each with a 100-hp engine, and ran them at full throttle night and day for an entire year, we would consume an amount of gasoline equivalent to about one *Q* of energy.

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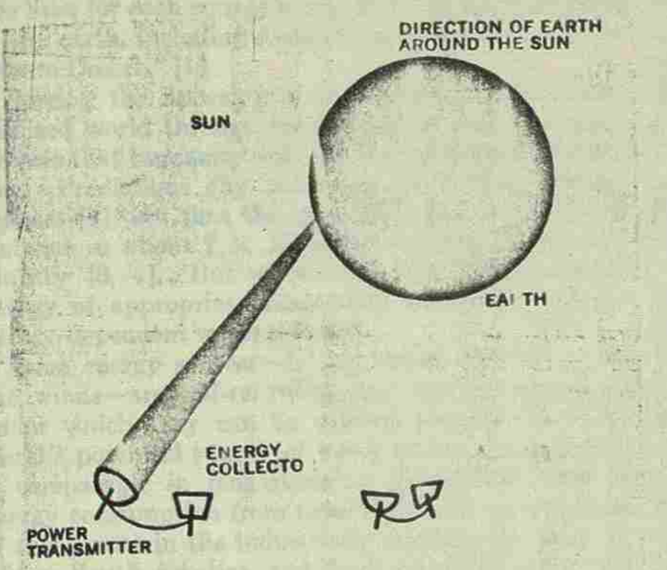
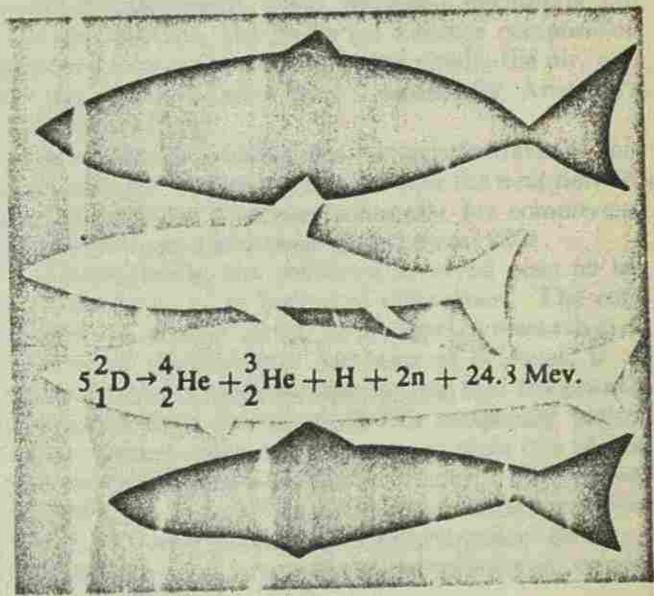




urve must follow one of three possible courses [1]:

- A continued rise for a brief period followed by a radual leveling to some stable figure which the world's nergy and material resources are capable of supporting or a long period of time.
- An overshoot of any possible stable level and a drop downward to eventually stabilize at some level compatible with the world's resources.
- Resource exhaustion and a general cultural decline. The curve would then reflect a population corresponding to the lowest energy consumption level of a primitive existence.

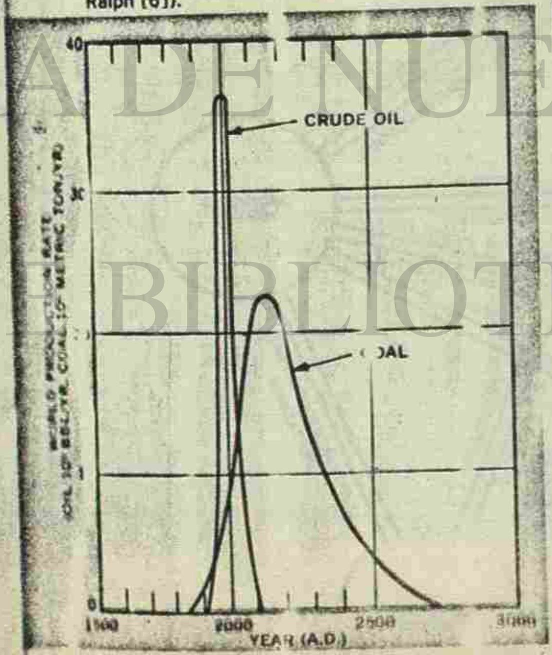
What is not possible is an unlimited population growth. Consider this: If the human doubling time of about 100 years were to persist, then in the year 2970 there would be about 10^{12} persons on earth. In fact, if the present world population were to double

TABLE
Reserves in Fossil Fuels

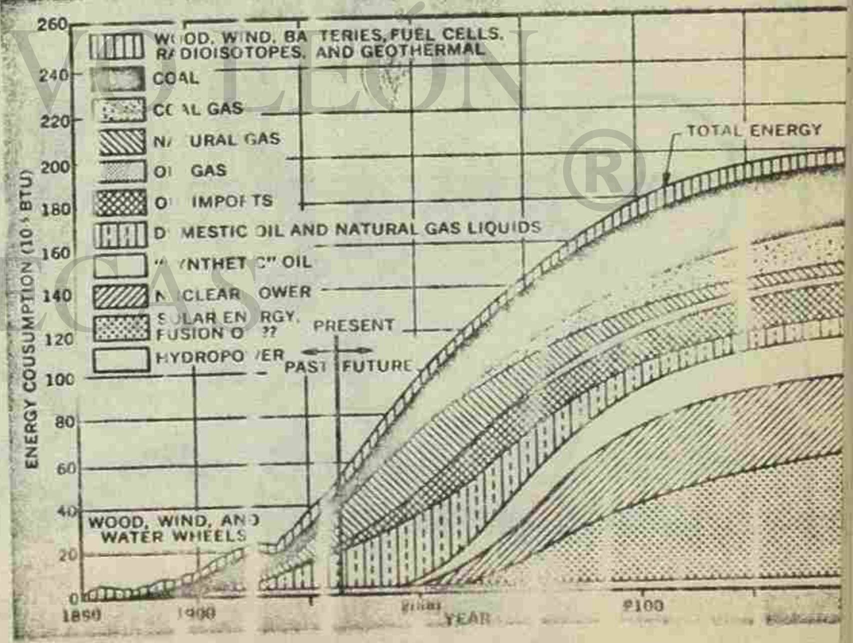
Fuel	U.S., Q	World, Q
Coal	4.600	18.00
Natural gas	0.310	2.11
Petroleum	0.278	1.70
Oil	0.298	1.70
Total	5.486	22.91

(From Duncan and McKelvey, U.S. Geological Survey, 1964 [5]).

World fossil fuel utilization rate. (From Ralph [6]).



Energy consumption in the United States, past, present, and future. (From Gaucher [7]).



but 15 or more times, "there would be in the year 2500, one man for each square meter on all of the land areas of the earth, including Antarctica, Greenland, and the Sahara Desert." [1].

Barring the apocalyptic destruction of the industrialized world through thermonuclear war, one must assume that humanity will opt for the second alternative. Predictions (by consensus of leading demographers [3]) are that the population of the earth will stabilize at about 7×10^9 sometime within the next century [3, 4]. But where then are the sources of energy of appropriate magnitude to sustain a high-energy-dependent world culture?

Some energy sources—falling water, the tides, and the winds—are self-renewing, but the circumstances under which they can be utilized are limited. The world's potential supply of water power, for example, is comparable in magnitude to the present rate of energy consumption from fossil fuels. However, most of this occurs in the industrially undeveloped areas of Africa, South America, and Southeast Asia, and could only be utilized by a parallel industrialization of these areas. In addition, although water power is capable of continuing for periods of geologic time, a practical limit in the case of large dams and reservoirs is set by the period of a few centuries required for the reservoirs to fill with sediments.

Geothermal and tidal energy are now being exploited in a few suitable sites around the world, but the ultimate amount of power from these sources does not promise to be larger than a small fraction of the world's present requirements. This leaves us with: nuclear energy, rock burning (fission) and sea burning (fusion); solar radiation; and the thermal heat of the oceans. As Alvin Weinberg, director of the AEC's Oak Ridge National Laboratory, notes, we must eventually fall back on "the sea, the rocks (of average composition since true ores will have been exhausted), the air, and the sun (equated with fire)...essentially Aristotle's four elements" [4].

Sea burning, although still a physicist's dream at this stage, may yet become a reality within the next decade. If so it could be a serious contender for commercial power in the quantities needed by the year 2001.

Technologically, the problems involved pose no insuperable physical or biological difficulties. The core problem, to paraphrase M. K. Hubbert, a research geophysicist of the National Academy of Sciences, is to uproot the deeply ingrained assumption that the growth rates which have characterized this temporary period are the normal order of things rather than one of the most abnormal phases of human history. This period is, he believes, "a brief transitional episode between two very much longer periods, each characterized by rates of change so slow as to be regarded essentially as periods of nongrowth."

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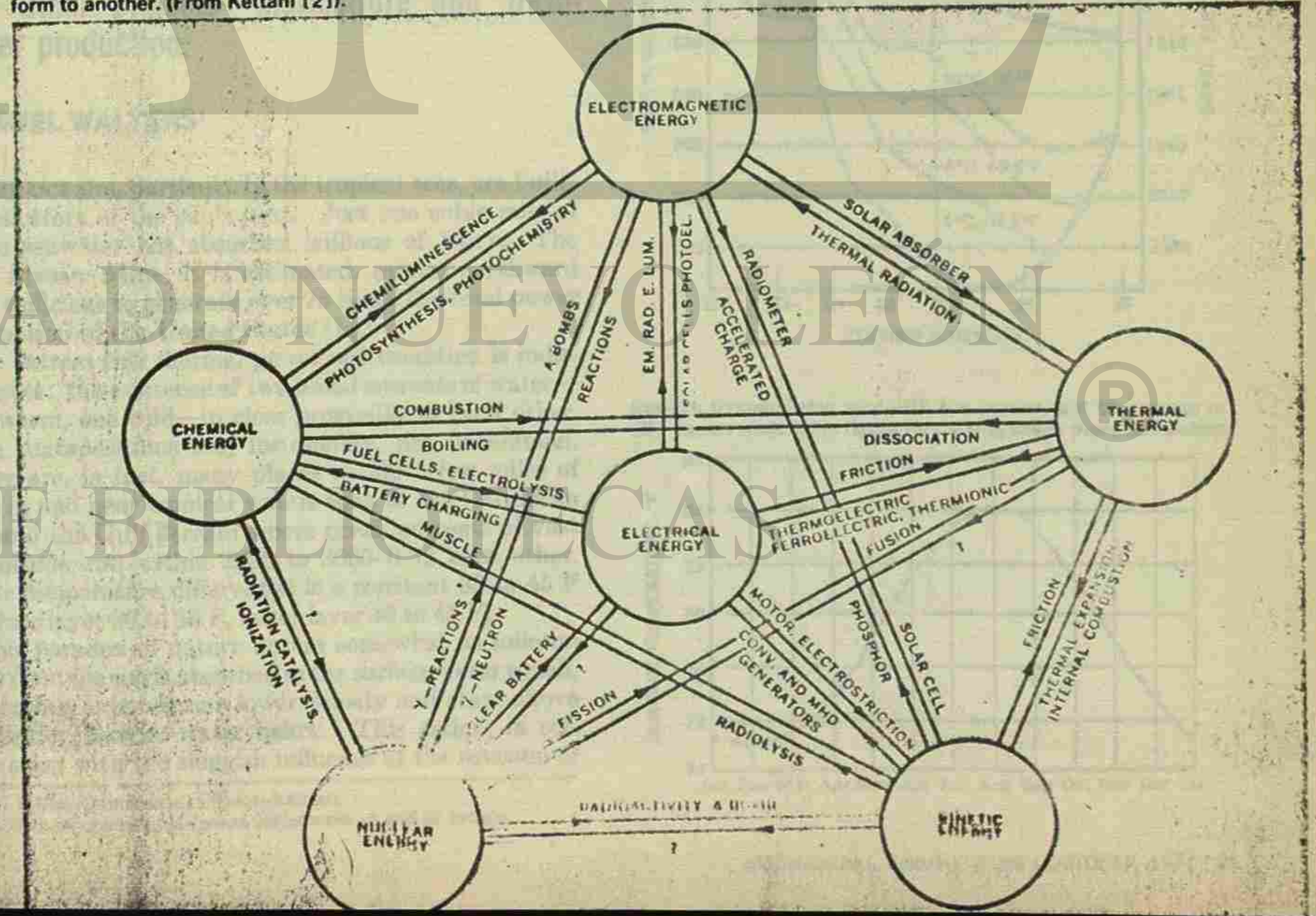
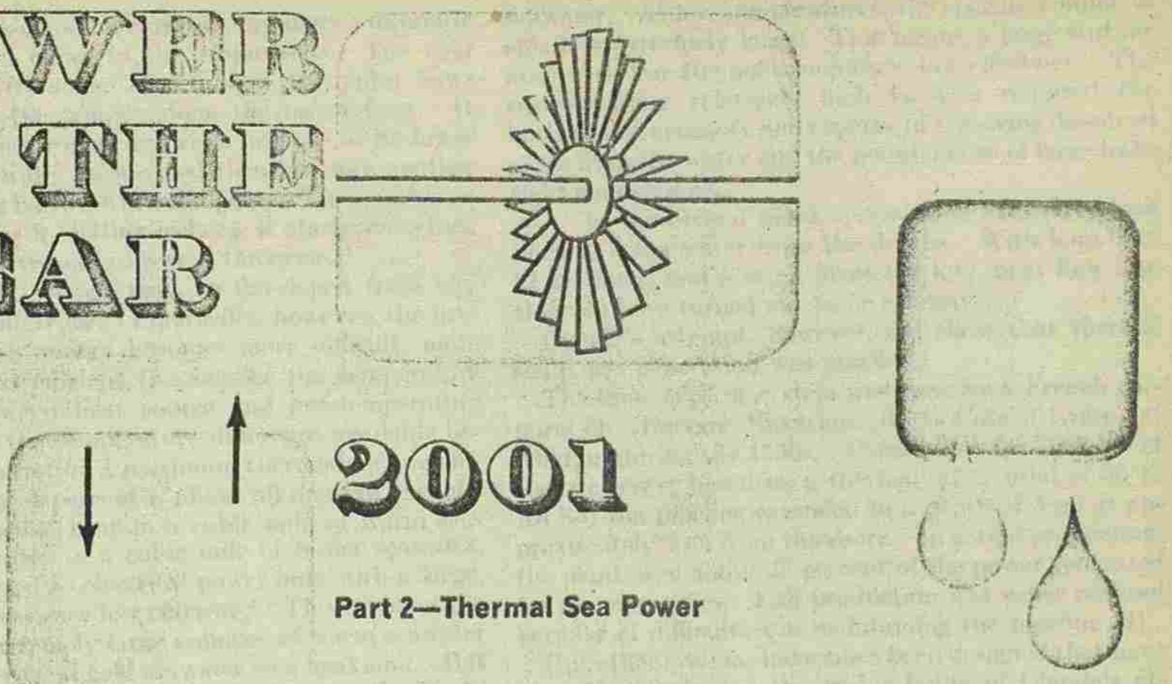
Energy Conversion Chart. The circles represent the different forms of energy and the arrows the ways of converting energy from one form to another. (From Kettani [2]).



POWER IN THE YEAR 2001



Part 2—Thermal Sea Power

Advances in underwater technology can now realize the old idea of generating power from temperature differences between tropical surface waters and colder currents flowing directly beneath. Such a tantalizing project is now underway in the Caribbean in combination with two other projects—mariculture and freshwater production.

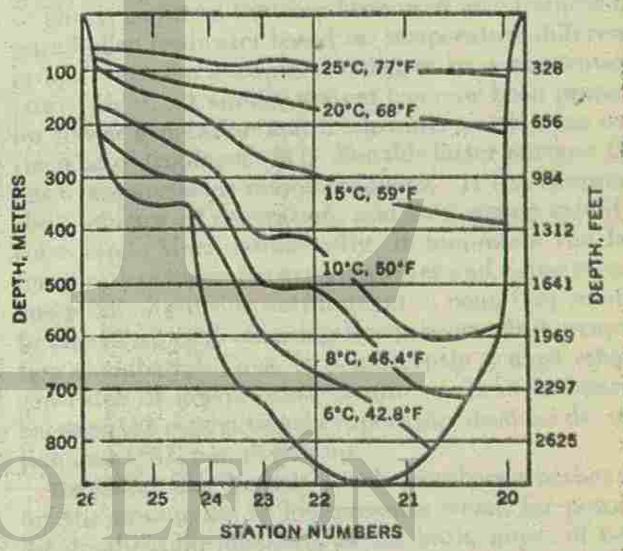
SAMUEL WALTERS[1]

THE OCEANS, particularly the tropical seas, are built-in collectors of the sun's heat. Just one cubic mile of warm seawater has absorbed trillions of Btu's. The Gulf Stream alone, it is estimated, carries northward heat sufficient to generate over 75 times the total power production of the United States [1].[2]

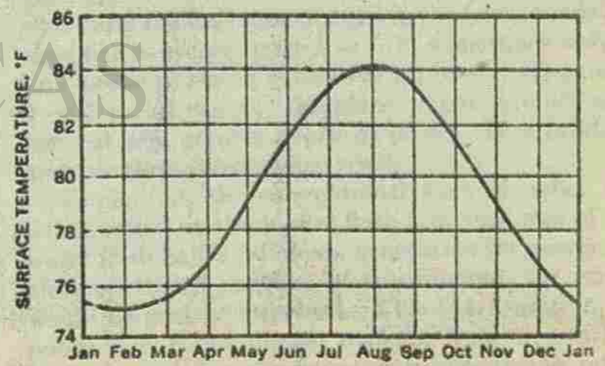
To extract this thermal power one condition is indispensable: the existence of two broad currents of water—one warm, one cold—in close proximity to each other. Such juxtapositions are, fortunately, not uncommon. There are, in fact, many places within a few miles of land in and near tropical waters such as the Caribbean Sea and the Gulf Stream where ocean currents of vast magnitude run within 2000 to 3000 ft of each other. Their temperature differential is a constant 35 to 45 F (surface layer 80 to 85 F, lower layer 40 to 45 F).

This paradox of nature occurs somewhat as follows: Heat from the sun is absorbed in the surface water which, on heating, expands to a lower density and stays above the colder, heavier water below. This action, in collaboration with the sluggish influence of the rotation of

Underwater temperatures in the straits of Florida, 30 miles from Miami. At 400 meters (1312 ft) the temperature is 43 F.



Surface temperatures vary with the season, but an average of 80F seems reasonable figure for making power plant calculation



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[1] Staff Editor, MECHANICAL ENGINEERING.

[2] Numbers in brackets designate References at end of article.

Part 3—Solar Power

The conjunction of several events—the space program, looming fossil-fuel depletion, degrading environment, and chronic power shortages—is slowly turning man's eyes toward the sun as the ultimate answer to our energy problems. Unlimited power via solar energy, gathered and focused earthward by satellites, may yet prove to be the greatest tangible benefit from the space program.

SAMUEL WALTERS[1]

Can the sun be harnessed for large-scale electric power? The energy potential is unbounded. The thermal power intercepted by the earth's diametral plane is 1.7×10^{17} w, which is about a hundred thousand times larger than the world's present installed electric power capacity. It also has the virtue of remaining nearly constant over time periods of millions of years.

Why then has solar energy not been tapped for this purpose? Principally because it is intermittent and too diffuse when it reaches the earth. (Night, clouds, and dust reduce the "sun time" to a "use time" of about 20 percent of the full time.) To "collect" it, large amounts of real estate, including an elaborate storage system, would be required.[2]

Obviously, the flux of solar energy should be intercepted not behind the "dirty basement window" of the cloud-shrouded night-affected earth, but in a satellite orbit high above the earth's surface where "real estate" has no meaning. Such an audacious idea has been proposed by Peter Glaser, Mem. ASME, and head of engineering sciences at the Arthur D. Little Laboratories [1].[3] A large space platform composed of a mosaic of solar cells hovers in synchronous orbit with the earth's rotation at a height of 22,300 mi (35,600 km). Solar energy, converted to electrical power by

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[1] Staff Editor, Mechanical Engineering.

[2] A solar-electric power plant of 1000-MW capacity, with a conversion factor from solar power to electrical power of 10 percent, would require a solar power input of 10,000 MW, or 10^{10} thermal w. According to Daniels [15] the average solar power at the earth's surface amounts to about 500 $\text{cal/cm}^2\text{/day}$. This, when averaged over a full day, gives an average solar power input of about 2.4×10^{-2} w/cm^2. Then the area of the earth's surface required to collect 10^{10} w of solar power would be $10^{10}\ \text{w}/(2.4 \times 10^{-2}\ \text{w/cm}^2) = 42 \times 10^{10}\ \text{cm}^2$, which would be 42 km^2, or a square area of 6.5 km per side.

[3] Numbers in brackets designate References at end of article.

the cells, flows through a flexible superconducting cable 2 mi in length to a satellite station where, converted to microwave energy, it is transmitted earthward unimpeded by atmosphere and clouds. It is then reconverted into d-c power by an antenna-rectifier array. The satellite is exposed to full sunlight all the time, except for a 1.2-hr interval every 24 hr for 25 days before and after equinox. By using two or even more satellites, properly spaced, the interruption of power during the 1.2-hr orbital night can be avoided. A continuous flow of power is thus assured, obviating the need for an energy storage system on earth.

An alternative plan is to place a space power station in a non-equatorial orbit with a seasonal rhythm pattern. The satellite power station is now no longer stationary with respect to the earth's surface but appears to move up and down above the southern horizon with a 24-hr period, the swing being the greatest during the equinox period.

How feasible is this scheme? Technological details have been discussed in various journals during the past few years. And recently the *Journal of Microwave Power* devoted an entire issue to the subject.[4] The consensus is that it is feasible, although in sheer engineering magnitude, such a system surpasses anything that has been realistically planned in the past.

Success would bring enormous rewards. An earth-girdling belt of solar cells 3 mi wide in synchronous orbit "would intercept 1.68 × 10^{15} watts of solar energy. *At the present level of technology,* eight percent of this power, or 1.34 × 10^{14} watts, could be provided in the form of d-c power to widely distributed locations over the surface of the earth. Such a power level would provide 1.17 × 10^{15} kw-hr of electrical energy per year, or over 200 times the . . . requirements for the year 1980" [1] (italics added). In addition, the directed beams could be used to hasten the evaporation of the seas or lakes, to control rainfall in selected locations, to increase hydropower potentials, to heat frozen areas, and for other beneficial uses [2].

Many of the working elements of such a system are close at hand. The first part of the project—development of the components for power generation, conversion, and transmission, would be similar to projects accomplished in the space program during past years. The other phases of the project, such as manufacturing the cells and other components in great numbers, transportation into orbit, control of attitude, orbital altitude, and temperature, operation of electric systems, and remote control of the station, would not be new in kind, but they would be of a scale and magnitude entirely without precedent. (This includes the use of humans to deploy and maintain the solar energy collector and microwave antenna.) For example, one NASA official [3] estimates that, based on present technology, a solar plant providing one-tenth of the present United States power needs would have a total mass exceeding 2[illegible]0 tons. In the not-too-distant future, improvement in efficiencies and lightweight designs could bring about "a reduction of this total mass to 50,000 or 20,000 tons, possibly even lower." These latter figures are within sight of the capabilities of earth-to-orbit shuttle systems now on the drawing boards.

System Outline

Basic elements of a solar power plant would consist of:

- Orbit characteristics to insure that the space platform is constantly exposed to solar radiation and that the radiating area can beam energy to any desired point.
- Solar energy conversion devices of high efficiency (80 percent or better).
- Transmitters capable of beaming the converted energy to an earth receiving station in a spectral region where minimum atmospheric absorption and scattering would be encountered.
- Earth receiving stations capable of accepting the required power density and transmitting the energy to power-distribution networks.

Orbit Location

The system consists of two satellites in synchronous orbit (22,300 mi altitude in an orbit parallel to the earth's equatorial plane). The satellites are about 21 deg out of phase and about 7900 mi apart to insure that one satellite is always illuminated during the time the other is in the earth's shadow, an event that occurs at least 1 hr each day for 25 days preceding and following the equinoxes. At this height and phase difference both satellites have a direct line of sight to the same point on earth.

Conversion Devices

Silicon solar cells have been the primary source of power for the Ranger, Mariner, and Surveyor spacecraft and almost all other unmanned space missions. As a commercial power-conversion device, however, the cell's usefulness is circumscribed by low efficiency and high costs, 10 percent and $4, respectively, for a cell 1 × 1½ in. Large-scale use demands a price better than 4 cents and an efficiency raised to 80 percent or better. But here again, one can assume accelerated progress based on the needs of large spacecraft now being designed for missions in earth orbit and for exploration of the moon and planets.

Solar-cell arrays already have grown, in the space of a few years, from a few square feet to several thousand square feet in large lightweight deployable arrays with power levels in the tens of kilowatts. And underway are new approaches to increase cell efficiency and reduce cell cost: optical concentrators to focus solar radiation on an individual solar cell in order to reduce the number of cells required, multicellular devices, and new manufacturing processes such as the manufacture of solar cells from webbed dendrite silicon [4] or from extrusion of a ribbon of silicon single crystals.

But most promising of all is the discovery of organic-type compounds with semiconductor properties. This could open the way to a major advance in photovoltaic efficiency.

According to Glaser and others [1, 5, 6] the maximum theoretical efficiency of 24 percent inherent in the inorganic single-crystal semiconductor may not pertain to organic-type materials where charge creation and motion depend upon the long-range intramolecular charge transfer in heavy molecules found in biological systems (nerves, for example). Says Glaser: "The semiconducting properties of such molecular systems may be very different in character from those of in-

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[4] Dec. 1970 issue.

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organic semiconductors, and hence may have no efficiency limitation."

The "difference in character" is based on the fact that charge creation and motion in the inorganic single-crystal semiconductor are related to the primary act of light absorption, whereas in high-molecular-weight organic systems there is a distinction between charge formation in a molecule and diffusion through the bulk medium. This means the charge may be transferred within the molecule before motion in an adjacent molecule or vacancy site occurs. Advantage can thus be taken of both the low-energy gap of such materials and a possible low rate of thermal backward diffusion of charge. Theoretically therefore, organic systems promise higher efficiency than inorganic semiconductors; they would weigh less and could be produced in large quantities at a much lower unit cost.

Attainment of a conversion efficiency of 80 percent will radically alter the prospects for commercial solar power. A space platform with 8.7 sq mi of collector area (3.3 mi in diameter) would be all that would be required to meet the power needs of the entire northeastern section of the United States [1]. The weight of the collector would then be reduced to about 160 tons, exclusive of supporting structures. This is well within the cost capability of a space program employing reusable shuttles to assemble space structures. Such an earth-to-orbit shuttle with a payload of 20 tons is now on the drawing boards [3].

Power Generation and Transmission

The illustration below shows the main elements of a system designed to beam 10,000 MW earthward, enough power to supply the city of New York and its environs. Because of the inefficiency of present-day solar cells, the solar collector spreads over a 25-sq-mi area. Solar energy is here gathered, converted to d-c electric power, and transmitted to the microwave generators along a transmission line 2 mi long. The line is superconducting to reduce weight and power losses. Along its entire length, multiple-stage refrigerators maintain the proper temperature. The line is also articulated to provide relative movement between the solar collector, which must maintain its orientation toward the sun, and the microwave generators, whose radiating antennas are beamed to a receiving antenna on earth.

The microwave power transmission system consists of three major parts:

- Microwave generation, that is, the conversion of the d-c power output from the solar cells into microwave power.
- Beam forming, that is, the forming of the microwave energy into a sharp beam by means of the transmitting antenna.
- Microwave collecting and reconversion, that is, a means of collecting the energy at the receiving point and then reconverting it back into ordinary electric energy.

At first glance, the very high power levels involved—10,000 MW of microwave power—appear incongruous. Microwave technology is usually identified with the low power levels common in the communications industry. However, efficient high-power tubes have been developed. The assumed 10^7 kw of microwave power can be generated in a phased array of 10,000 amplitrons, each with an output power of 1000 kw [7, 8]. Such an array would reduce the rating of the individual tubes to the point where their design would be consistent with a modest extension of existing tube technology.

Earth Receiving Station

The capture and conversion of the 10,000 MW of microwave power beamed earthward from space is by "rectenna" (contraction for rectifying antenna), a device that combines the functions of a receiving antenna and rectifier. It is a large dipole receiving field several square miles in area made up of highly efficient solid-state rectifiers dispersed throughout the array and terminating in small apertures. The array, as a consequence, is relatively non-directive, which eliminates pointing problems and minimizes mechanical tolerances [7, 9]. The converted d-c power is then fed into a distribution network through superconducting transmission lines. Such networks have already received considerable attention, and research is being performed on this method for electric power transmission in this country and abroad.

Although the power densities in the microwave beam (roughly 1 w/sq cm, an order of magnitude greater than the solar radiation received on earth) may damage objects or living tissues that might enter the beam, they are not high enough to cause major destructive effects. Safety devices would have to be devised and regulations established to prevent entry of objects or living beings into the beam. The problem of safety

Courtesy of Arthur D. Little Inc.

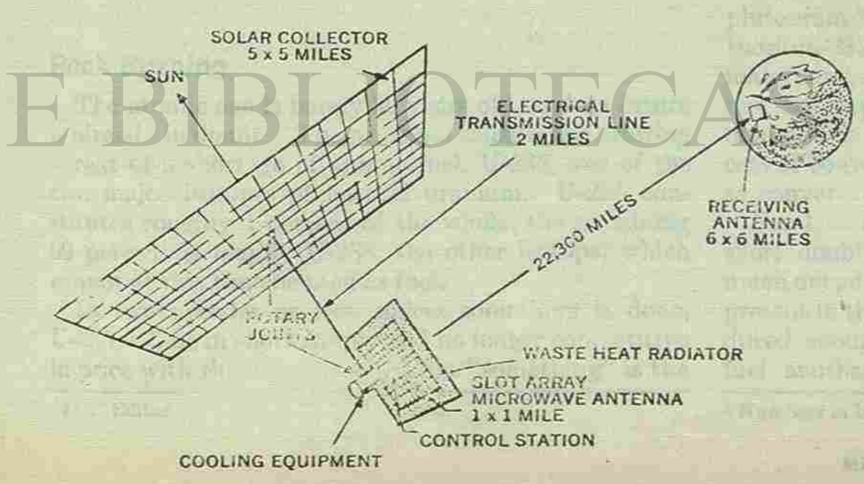
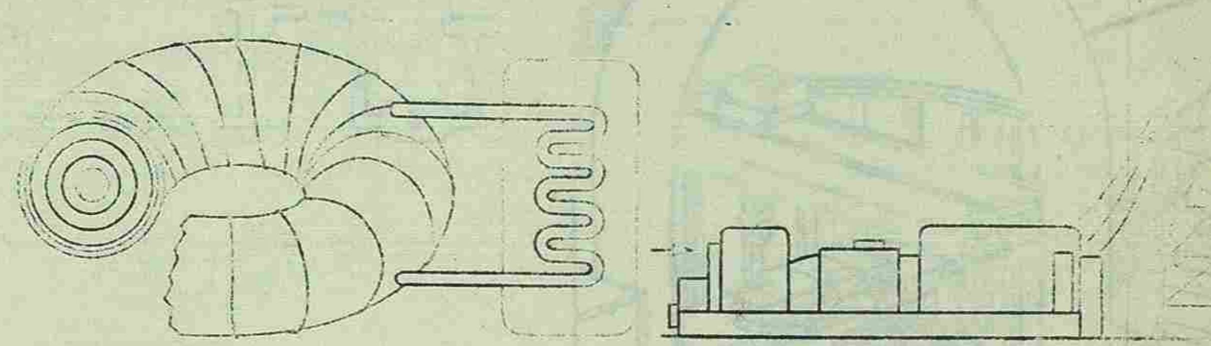


Diagram of the main elements of a satellite solar power station designed to produce 10,000 MW, enough power to supply the city of New York and its environs.

POWER IN THE YEAR 2001



Part 4—Rock Burning and Sea Burning

Dispersed in the rocks of the earth are enormous quantities of "fertile" low-grade uranium and thorium ores. These will be converted to fissionable fuel in an experimental breeder reactor, a power plant that produces more nuclear fuel than it consumes. Success would assure a supply of low-cost energy for thousands of years. Our finite reserves of coal, oil, and gas would then be used as sources of organic molecules rather than as sources of heat. As for "sea burning," the process of extracting energy through fusion of the heavy isotopes of hydrogen, this is still a physicist's dream, but the lineaments of a practical device can be discerned in the emphasis on its scientific feasibility and some rudimentary thought on the technological, economic, and social aspects of commercial fusion power.

SAMUEL WALTERS[1]

Rock Burning

The atomic age is barely 30 years old, and its future is already in doubt. The principal cause is the growing threat of a shortage of atomic fuel, U-235, one of the two major isotopes of natural uranium. U-235 constitutes roughly 1 percent of the whole; the remaining 99 percent is mainly U-238, the other isotope, which cannot at this time be used as fuel.

In two decades or less, unless something is done, U-235 will be in short supply and no longer competitive in price with the [illegible]. That "something" is the breeding reactor, so called because it produces more nuclear fuel than it consumes. The now-wasted U-238, along with low-grade thorium ores, would be converted through neutron bombardment into fissionable fuel from the dwindling supply of U-235.

At the present time, U-235 in the form of a 5-lb fuel rod is already worth about a third of its weight in solid gold. The refining process—separating U-235 from U-238—is an expensive operation because both have the same chemical characteristics. Huge $800-million separation plants do the job. The end product is a slightly enriched uranium containing about 3 percent U-235. The utilities pay the price because the potential of a single fuel rod is the heat equivalent of 6000 tons of coal [1].[2]

Breeding Reaction

The breeding reaction goes as follows: Uranium-238 (or thorium-232) is subjected to neutron bombardment in a reactor whose initial supply of fuel is uranium-235. Uranium-238 absorbs a neutron and is converted to U-239. The latter, by two short-lived radioactive transformations, changes spontaneously, first to neptunium-239, and then to plutonium-239. Likewise, thorium-232 absorbs a neutron and is transformed into thorium-233. This, in turn, changes radioactively into protoactinium-233 and then into uranium-233 [2].

Because they are fissionable, U-233, U-235, and plutonium-239 are called fissile isotopes. U-238 and thorium-232, on the other hand, are known as fertile materials because they are not themselves fissionable, but are capable of being converted into previously nonexistent isotopes which are fissionable. The process of converting fertile into fissile materials is known as conversion.

Fundamental to a successful breeding program is a short doubling time (the time required to produce as much net additional fissionable material as was originally present in the reactor). The reactor thus w[illegible] produced enough fissionable material to [illegible] fuel another identical reactor. An efficient [illegible]

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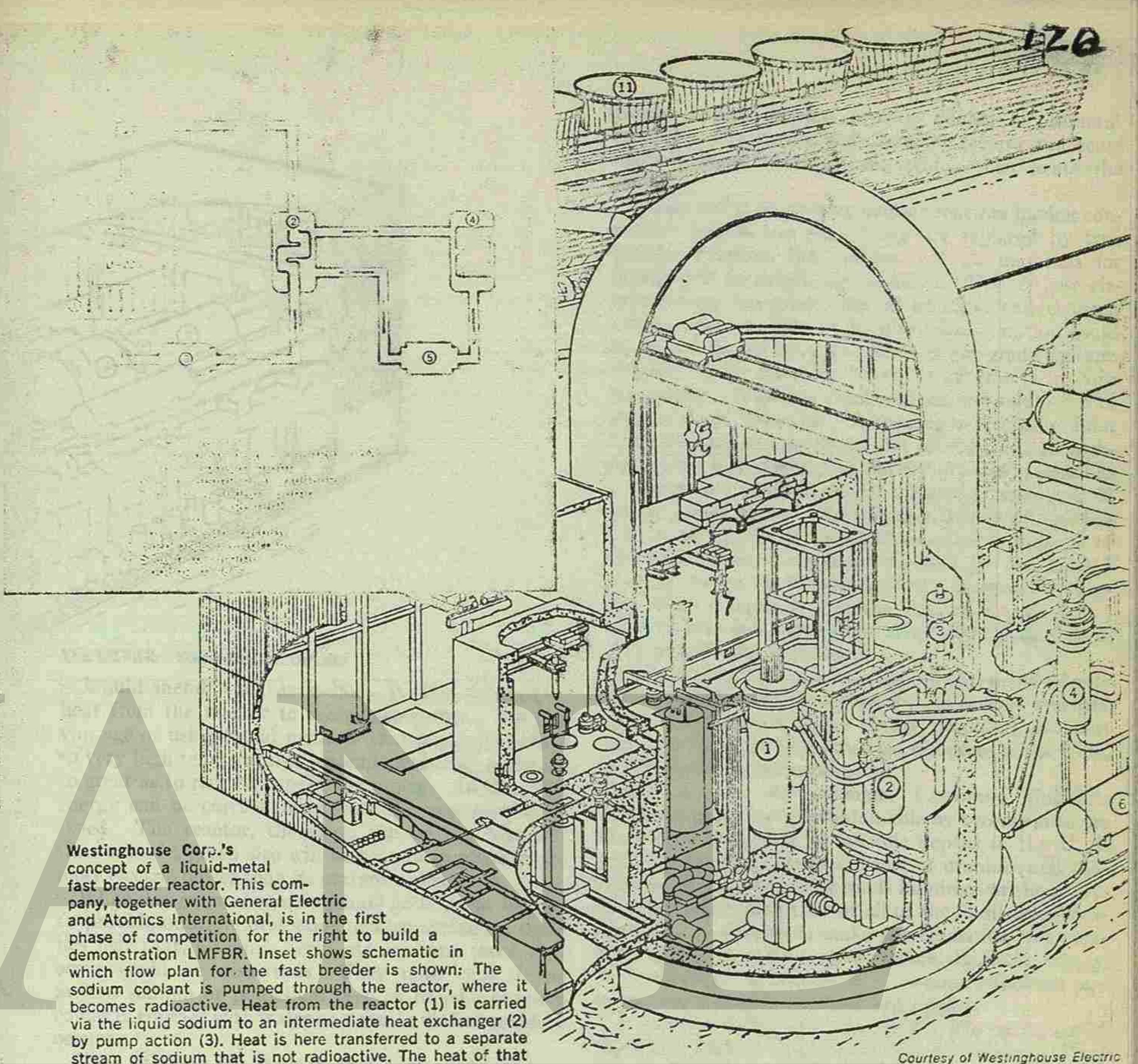
[1] Staff Editor, [illegible]ING.

[2] Numbers in brackets designate References at end of article.



Westinghouse Corp.'s concept of a liquid-metal fast breeder reactor. This company, together with General Electric and Atomics International, is in the first phase of competition for the right to build a demonstration LMFBR. Inset shows schematic in which flow plan for the fast breeder is shown: The sodium coolant is pumped through the reactor, where it becomes radioactive. Heat from the reactor (1) is carried via the liquid sodium to an intermediate heat exchanger (2) by pump action (3). Heat is here transferred to a separate stream of sodium that is not radioactive. The heat of that stream is used to produce steam (4). Steam is piped out (10) to drive the turbogenerators.

Courtesy of Westinghouse Electric

reactor will have a doubling time in the range of 7 to 10 years [3].

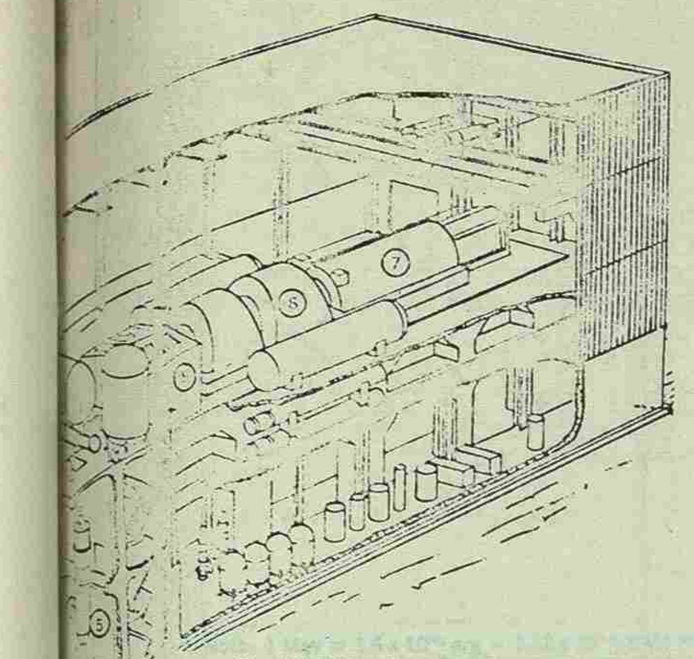
As far as energy production is concerned, the thermal energy produced per gram by either plutonium-239 or uranium-233 is approximately the same as that produced by uranium-235: about 8.2×10^{10} joule per gram. This is the equivalent to the heat of combustion of approximately 2.8 metric tons of coal or 14 bbl of crude oil [4].

Breeder Systems

The breeding concept is almost as old as the nuclear chain reaction, and the technology itself is now largely at hand. Two different breeder systems are involved, depending on which raw material is being transmuted: the thermal breeder and the fast breeder. The thermal breeder uses slow neutrons and operates best on the thorium-232–uranium-233 cycle (usually called the thorium cycle). The fast breeder uses more-energetic [illegible] best on the uranium-238–plutonium-239 cycle (the uranium cycle) [3].

In the United States and several other countrie fast breeder reactor cooled with liquid metal—th called LMFBR (liquid-metal-cooled fast breede actor)—has been given priority. Under AEC pices, something like a "crash program" is unde to develop a commercial LMFBR power plant by

We are not, however, putting all our atomic m in one basket. The utilities companies have poo sources to develop a gas-cooled fast breeder that uses pressurized helium as the coolant. In addition, other types of breeders are under d ment. The Oak Ridge National Laboratory is w on a molten-salt breeder reactor based on the th 232–uranium-233 cycle. Because it uses thorium raw material, this reactor would complemen LMFBR, which uses uranium-238. Another pr is attempting to modify the present type of light- reactors by adding blankets of fertile materia greatly increase the conversion ratio [4].



The LMFBR: Some Design Details

Liquid metal, such as sodium, is used to transfer heat from the reactor to steam generators. The advantage of using liquid metal is that it can be heated to very high temperatures without producing pressures so great as to risk rupture of the piping. In this way, energy can be carried away from the reactor at high speed. The reactor, therefore, can be run "faster"; thus one of a given size will be able to generate much more electric power than its current counterpart.

While designers of atomic plants go to great lengths to provide multiple protection against accidents, skeptics fear that, although accidents are rare, those that occur could be disastrous. They note that if the molten sodium or potassium used in breeder reactors comes in contact with water or steam, a violent reaction occurs.

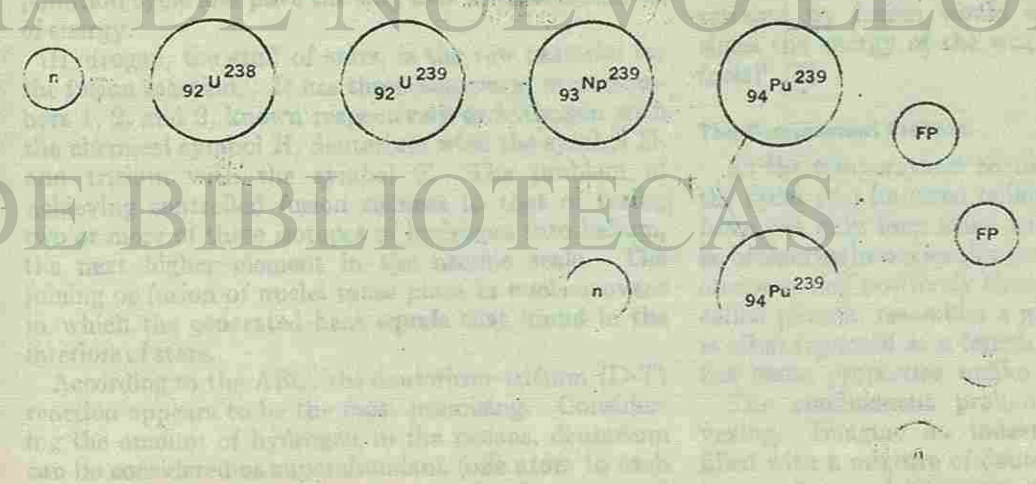
Thus, if there is a leak in that part of the system where the liquid metal is used to heat steam, it could be catastrophic. To isolate the reactor from such a danger, typical designs provide double liquid-metal systems. One carries heat from the reactor and heats another liquid-metal system, which then heats the steam.

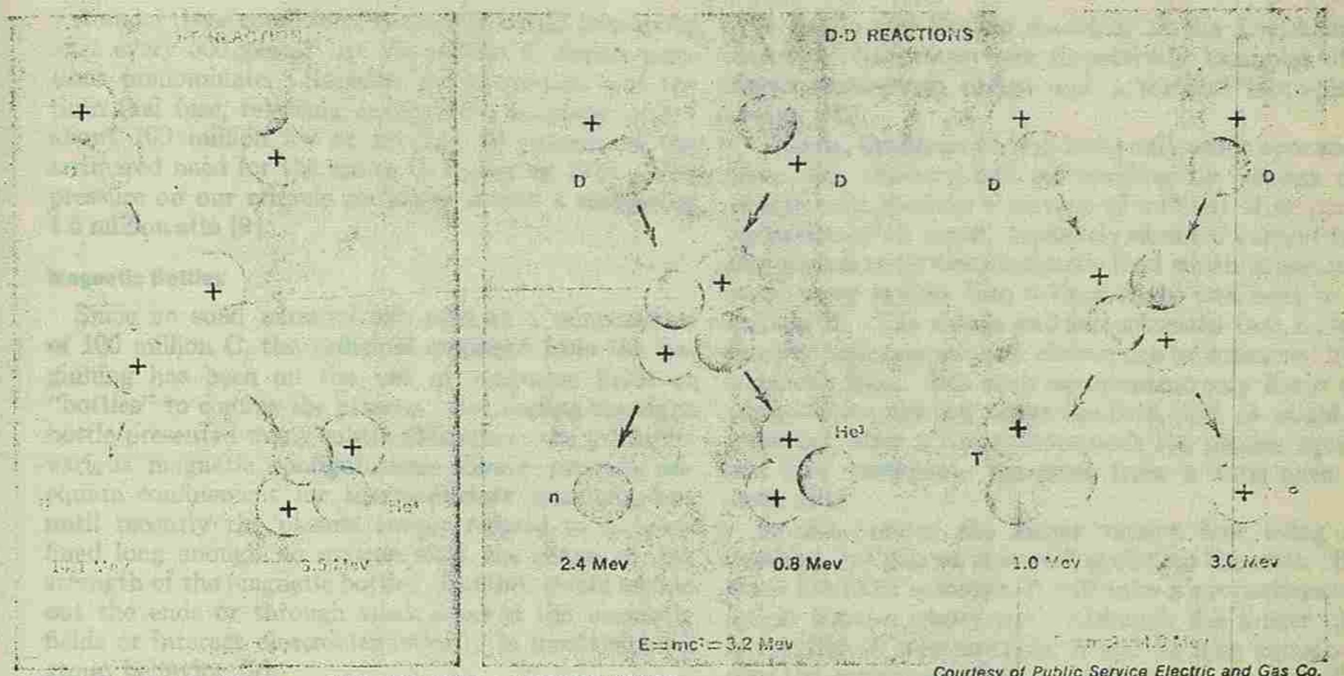
When and if all present nuclear reactors having conversion factors less than unity are replaced by true breeder reactors, the problem of raw materials for energy will be drastically modified. Under these circumstances, low-grade ores of uranium and thorium which cannot at present be given consideration could be used. As one example, there are low-grade thorium deposits to be found in the Conway granite in New Hampshire. This is a granite which crops out over an area of about 300 sq mi. According to studies by John A. S. Adams and associates, and cited by M. K. Hubbert of the U. S. Geological Survey [5], this granite has a remarkably uniform thorium content, averaging 56 grams per metric ton. In this case, 1 cu m of rock has a mass of 2.7 metric tons and contains 150 grams of thorium. Since the energy released by fissioning 1 gram of thorium is substantially the same as for uranium, the fuel equivalent of the thorium contained in 1 cu m of rock is equivalent to about 400 metric tons of coal, or 2000 bbl of crude oil.

Should the whole area be quarried to a depth of only 100 m (330 ft) and the thorium used in breeder reactors, the fuel equivalent of the energy produced, Hubbert notes, would be 20 times the coal resources of the U. S., or 750 times the resources of oil.

This is only one example. Continues Hubbert: "The energy potentially obtainable by breeder reactors from rocks occurring at minable depths in the U. S. and containing 50 grams or more of uranium and thorium combined per metric ton is hundreds or thousands of times larger than that of all of the fossil fuels combined. . . . Failure to make the transition to a complete breeder reactor program before the initial supply of uranium-235 is exhausted . . . would constitute one of the major disasters in human history."

It remains to be seen, however, if the problems of thermal pollution and public fear of "excursions" of venting radioactivity can be sufficiently allayed to permit the proliferation of atomic power to the required need.





Note: 1 Mev = 1.6×10^{-6} erg = 1.52×10^{-16} BTU = 4.45×10^{-20} kwhr
Also possible is a D-He^3 reaction producing He^4 + H + 18.3 Mev.

Courtesy of Public Service Electric and Gas Co. and Princeton's Plasma Physics Laboratory.

Fusion reactions. A deuterium nucleus can fuse with a tritium nucleus (left) to form helium-4 and a neutron. It can also fuse in two other ways with another deuterium nucleus (right) to form helium-3 and a neutron or tritium and a proton (ordinary hydrogen nucleus).

These fears, if not all the "facts" on which they are founded, are very real. Against the background of these fears, siting problems become acute dilemmas. As TVA's manager of power, G. O. Wessenauer, put it to an Atomic Industrial Forum workshop last year: "An ideal site is one for which there is no evidence of any seismic activity over the past millennia; is not subject to hurricanes, tornadoes, or floods. It should be in an endless expanse of unpopulated desert with an abundant supply of very cold water flowing nowhere and containing no aquatic life. Most important, it should be adjacent to a major load center."

Sea Burning

To many scientists, the breeder reactor described above is only an interim technology, a holding action until they can master the difficult art of controlling thermonuclear fusion. Success will break the energy-pollution cycle and pave the way to a limitless reservoir of energy.

Hydrogen, the stuff of stars, is the raw material for the fusion reaction. It has three isotopes of mass numbers 1, 2, and 3, known respectively as hydrogen with the chemical symbol H, deuterium with the symbol D, and tritium with the symbol T. The problem of achieving controlled fusion reduces to that of fusing two or more of these isotopes of hydrogen into helium, the next higher element in the atomic scale. The joining or fusion of nuclei takes place in nuclear ovens in which the generated heat equals that found in the interiors of stars.

According to the AEC, the deuterium–tritium (D-T) reaction appears to be the most promising. Considering the amount of hydrogen in the oceans, deuterium can be considered as superabundant (one atom to each 6700 atoms of hydrogen). It can also be extracted easily. There is sufficient lithium in the United States alone to insure, via the D-T reaction, an energy content more than fivefold that inhering in the world's fossil fuels [6].

But if fusion were accomplished in a D-D reactor, one-fourth of the energy output could be taken out directly as electricity, an important advantage, plus the fact that deuterium is far more bountiful than tritium. One cu m of water contains about 10^{25} atoms of deuterium having a mass of 34.4 grams and a potential fusion energy of 7.94×10^{12} joule. According to Hubbert, this is equivalent to the heat of combustion of 300 metric tons of coal or 1500 bbl of crude oil. Since a cubic kilometer contains 10^9 cu m, the fuel equivalent of one cubic kilometer of seawater is 300 billion tons of coal or 1500 billion bbl of crude oil. Hubbert sums up fusion's potential: "The total volume of the oceans is about 1.5 billion cubic kilometers. If enough deuterium were withdrawn to reduce the initial concentration by 1 percent, the energy released by fusion would amount to about 500,000 times the energy of the world's initial supply of fossil fuels!" [7].

The Confinement Problem

At the temperatures required for fusion ignition, on the order of a hundred million degrees C, all materials have not only long since vaporized, but ionized, that is, broken up into a seething cloud of negatively charged electrons and positively charged nuclei. This mixture, called plasma, resembles a gas in some respects, but it is often regarded as a fourth state of matter because it has some properties unlike gases, liquids, or solids.

The confinement problem has been particularly vexing. Imagine an indestructible 1-liter container filled with a mixture of deuterium and tritium at room temperature and 1 atm pressure. Heating the mixture to 100,000 C will pull atoms apart producing a plasma

But under these conditions, two nuclei would fuse about once every 500 years! At 100 million C, fusion reactions predominate. Rapidly, the deuterium and tritium fuel fuse, releasing energy at a fantastic rate—about 100 million kw or roughly 10 percent of the estimated need for the entire U. S. during 1975. The pressure on our miracle container is now a staggering 1.5 million atm [8].

Magnetic Bottles

Since no solid material can exist at a temperature of 100 million C, the principal emphasis from the beginning has been on the use of magnetic fields or "bottles" to confine the plasma. But finding the right bottle presented many subtle difficulties. In principle, various magnetic configurations should provide adequate confinement for thermonuclear reactions, but until recently the plasma simply refused to be confined long enough no matter what the shape or the strength of the magnetic bottle. It either would escape out the ends or through weak areas in the magnetic fields or interact electromagnetically in unanticipated group behavior [9].

In general, magnetic bottles fall into two types: linear (open) or toroidal (closed). In the open type, squeezing fields of magnetism form a partial or leaky "stopper" preventing plasma from escaping out the ends of the tube. In the closed type, the tube is bent into a doughnut shape, or toroid, and here the purpose of the magnetic fields is to confine the plasma to the middle of the tube, away from material walls.

A number of existing systems are based on these types, and are classified on the basis of increasing plasma density. Three general systems are described: the theta pinch, the magnetic mirror, and the torus.

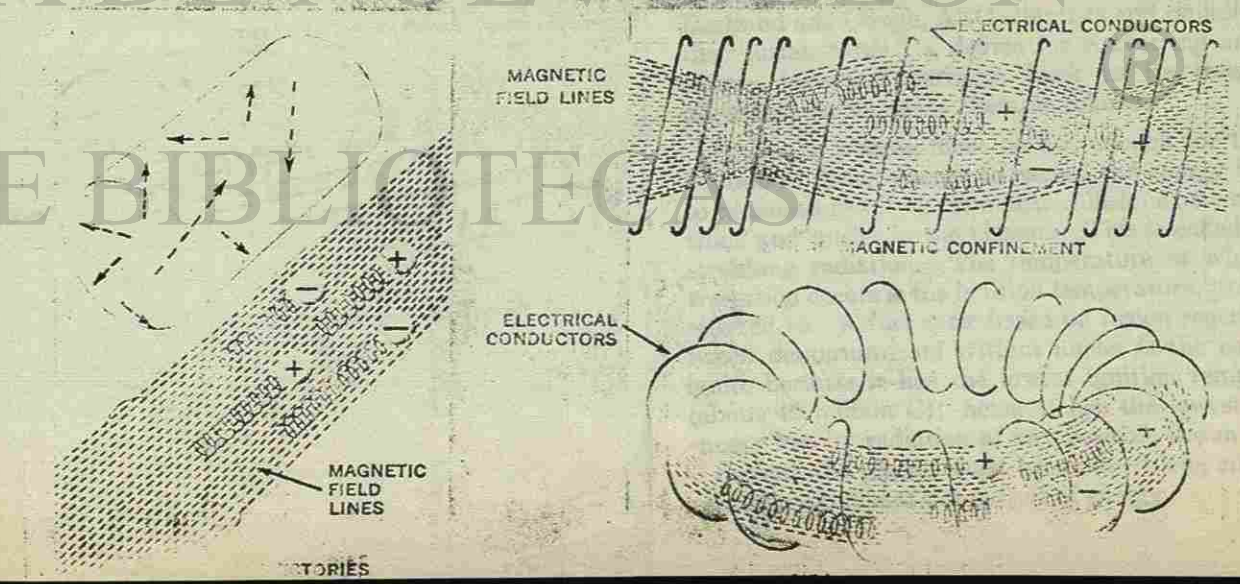
Theta Pinch. This is a high-density plasma container, which is defined as one in which the plasma pressure is comparable to the magnetic field pressure. This device has been built in both the linear and toroidal forms. Here the electric current is in the theta, or azimuthal, direction (around the axis) and the resulting magnetic field is in the zeta, or axial, direction (along the axis). The Scylla and Scyllac machines at the Los Alamos Scientific Laboratory are respectively examples of a linear theta-pinch design and a toroidal theta-pinch design [10].

To date, the linear version is the only one in operation. Here, the one-turn coil surrounding the plasma discharge tube receives a current of millions of amperes; induction of an equal, oppositely directed current into the plasma results in a magnetic field which causes it to pinch very rapidly into a cigar shape and heat to 50 million K. The device has demonstrated that a high-density high-temperature plasma can be contained by a magnetic field. But such containment only keeps the plasma from moving across the field, and, as would be expected, after a few microseconds the plasma squirts out like toothpaste squeezed from a tube open at both ends.

In the case of the longer version now being assembled, the plasma must still squirt out the ends. But since the path is longer, it will take a proportionately longer time to empty out. Although this longer time is roughly 10 microseconds, it will be long enough to give the experimentalists a chance to see whether this cigar-shaped plasma is widening out, i.e., spreading *across* the field. To make a reactor out of this approach, the device would have to be tens of miles long—too long and too expensive to be of practical interest. The interest, therefore, is in bending it around into a doughnut or torus. This has not yet been done, but is the main objective of the Scyllac experiment for the next several years [5].

Magnetic Mirror. This is a medium-density plasma container. In this device a linear magnetic bottle is partially "stoppered" at the ends by magnetic "mirrors" (regions of somewhat greater magnetic-field strength that reflect escaping particles back into the bottle). In addition, since mirror devices are necessarily very leaky, extra current-carrying structures are often used to improve the stability of the plasma. experiments being conducted are of two kinds. a warm plasma is "hypodermically" injected into a magnetic mirror, then heated and made more dense

There have been many configurations devised in the past two decades to confine plasmas for fusion research. All fall into two general types: linear (open) or toroidal (closed). In the open type, squeezing fields of magnetism form the sole "stopper" preventing plasma from escaping out the ends of the tube. In the closed type, the tube is bent into a doughnut shape, or torus and here the purpose of the magnetic fields is to confine the plasma to the middle of the tube, away from material walls.

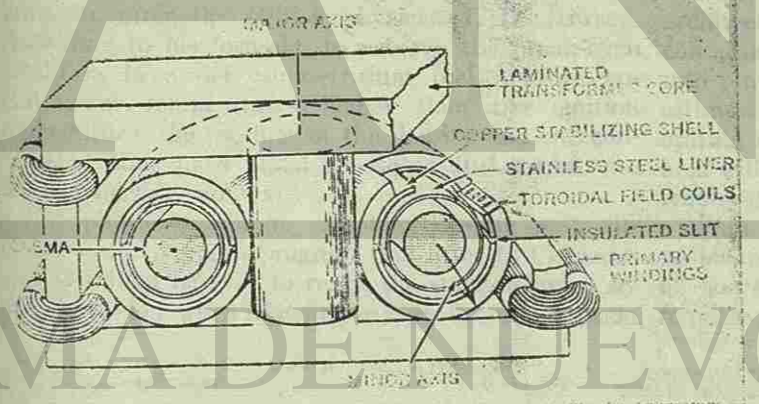


by compression. Containment has been achieved, but there are some enhanced losses, which would be a little too large for a reactor. In the second method, careful slow injections, utilizing plasma accumulated over many seconds, can control both direction of particle motion and energy spread. By such means, it is hoped that the causes of enhanced losses can be identified and perhaps eliminated.

Tokamak. This is a medium-density plasma container of the toroidal type. It represents a qualitative jump in our knowledge and skill in containing the maddeningly complex plasma long enough to achieve a fusion reaction. This machine, developed by the Russians a couple of years ago, has heated plasma to 10 million K while maintaining densities of 30,000 billion particles per cubic centimeter for 1/50th of a second, the closest approach yet to a fusion reaction. The Soviet claim met with some skepticism, since plasma measurements are notoriously difficult to make and interpret. A British team, however, from Culham Laboratory, confirmed that the temperature was indeed at the level claimed by the Soviets [11].

Tokamak also differs from earlier U. S.–built toroids called Stellerators in that it is axially symmetric, closer to the ideal doughnut shape of a torus. Raising the temperature of Tokamak plasmas to thermonuclear values appears to be a problem, however, which the Russians believe can be overcome solely by larger versions. U. S. physicists, while not agreeing that scaling-up the size of the Tokamak device will in itself achieve the desired fusion reactions, believe the Tokamak configuration is promising. One Tokamak has been built at the Princeton Plasma Laboratory and has been in operation since May, 1970. Another will go into operation at Oak Ridge by the end of this year and two more will shortly come into operation at the University of Texas and at M. I. T. New Princeton results indicate that superiority of Tokamak over U. S. configurations may simply be that Tokamaks are larger [5].

Tokamak, U. S. style. This is a toroidal plasma confinement device and has been in operation at the Plasma Physics Laboratory at Princeton, N. J., since May, 1970. A cutaway cross section of the Tokamak configuration is shown above.



Courtesy of Princeton's Plasma Physics Laboratory

A Light Approach

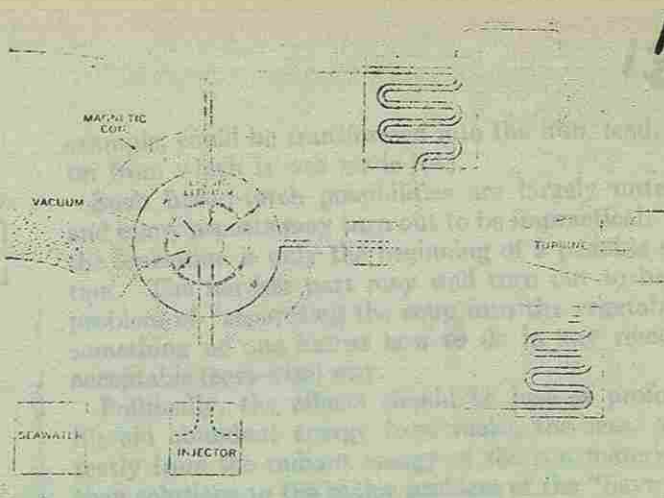
Another great leap forward in fusion technology within the last few years has involved the introduction of lasers for generating and heating plasma. In addition to being easier to analyze than cyclotron- or neon-tube-generated plasmas, laser-generated plasmas are hotter, denser, and purer; laser beams cross magnetic fields, without disturbing them, so that plasma production is achieved quickly and completely without leftover neutral debris. A frozen pellet of hydrogen or one of its isotopes is instantly vaporized and completely ionized by a powerful laser pulse lasting less than a billionth of a second; the pulse must be that fast to deposit energy in freely expanding plasma before it becomes transparent to the laser beam. Dr. Moshe Lubin of the University of Rochester suggests that extremely rapid lasers could confine plasmas as well as generate and heat them, obviating entirely the need for magnetic fields with their instabilities and losses [12]. He proposes an inertial confinement device in which a pellet of deuterium and tritium, dropped near a blanket of lithium, would be vaporized in picoseconds by an ultra-short, ultra-strong laser pulse. The resulting fusion would produce neutrons that bombard the lithium blanket, generating tritium atoms which could be cycled back into the reactor to sustain a closed-loop reaction. Although present-generation lasers are neither fast enough nor powerful enough to initiate such a reaction, they have already generated very small amounts of fusion reactions [12].

The Fusion-Power Balance

What are the fundamental requirements for a meaningful release of fusion energy in a reactor? Eastlund and Gough, AEC scientists and proponents of the "fusion torch," a device for converting any substance, including garbage, back to its constituent elemental atoms, state them as follows:

First, the plasma must be hot enough for the production of fusion energy to exceed the energy loss due to radiation resulting from near-collisions between electrons and nuclei in the plasma. This is called bremsstrahlung radiation. The temperature at which this transition occurs is the ignition temperature, previously referred to. A fuel cycle based on fusion reactions between deuterium and tritium nuclei is the easiest to ignite because it has the lowest ignition temperature (about 40 million C); hence it has the lowest rate of energy loss by radiation of any possible fusion fuel.

Second, the plasma must be confined long enough to release a significant net output of energy.



Fusion reactor based on a deuterium–tritium fuel cycle. Such a fuel would release approximately 80 percent of its energy as highly energetic neutrons. This neutron energy would be absorbed in a liquid-lithium shield, circulating the liquid lithium to a heat exchanger where water would be heated to produce steam to drive a conventional turbogenerator. Reactor core could be either linear or toroidal.

Third, the energy must be recovered in a useful form.

Today, they report, a [illegible] number of different devices have either [illegible] the deuterium tritium ignition temperature or come close to it. The main difficulties—energy-loss processes involving impurity atoms entering the plasma from the walls of the container—have been solved by a large research effort in vacuum and surface technology [13].

As for confining the plasma long enough to release a significant net amount of energy, Eastlund and Gough report that large containment devices have reduced the plasma instabilities responsible for large-scale plasma leakages to such low amplitude that other, more subtle effects, such as convective plasma losses and magnetic-field imperfections, can now be studied. Such studies have convinced physicists that there exists no basic law of physics that prevents plasma confinement for times long enough to release significant net fusion energy. In fact, "classical" or ideal plasma confinement has been achieved in several machines at low temperatures, a condition which, if extrapolated to fusion temperatures, would yield a plasma loss rate much lower than that required for a fusion reactor.

Lawson's Criterion

The twin achievements of ignition temperature and adequate confinement time have not, however, produced a sustained fusion reaction. Reason: Each of these achievements was produced in machines designed specifically to achieve one goal or the other, but not both.

To surpass the "break-even" point or power balance, a point beyond which the reactor is capable of producing more energy than it consumes, a machine must combine both achievements. This point is called Lawson's criterion, after the British physicist J. D. Lawson. According to his formula, to achieve the break-even condition in a deuterium–tritium fuel mixture operating at temperatures higher than the ignition temperature, the product of the density and the confinement time must equal or exceed 10^{14} sec/cu cm. No such machine now exists.

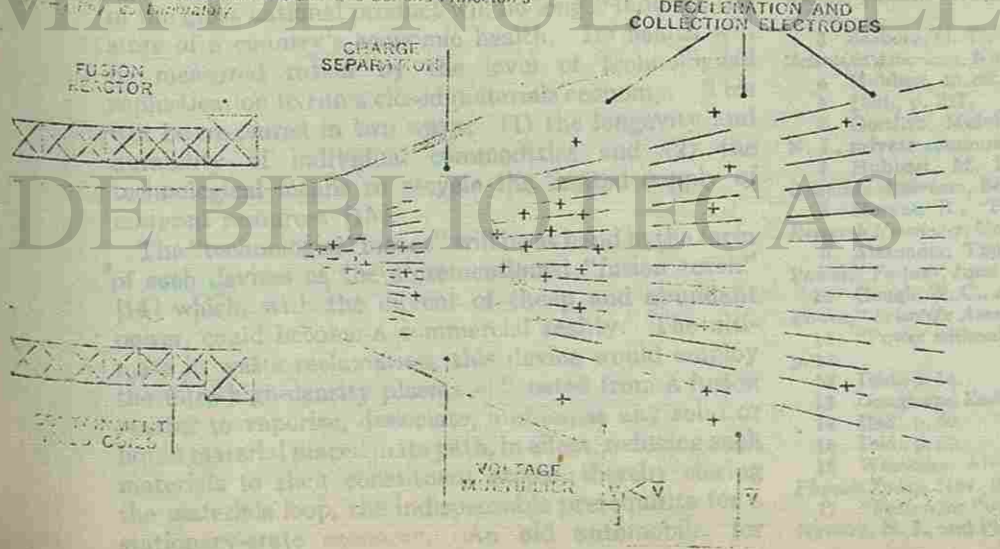
But physicists remain sanguine, despite past difficulties of a research program that after two decades and $1 billion has yet to reach the stage attained by nuclear fission when the first self-sustaining reaction went critical under a University of Chicago squash court. The main reason for such optimism is the extraordinary progress that has been made recently by various groups in learning how to raise the combination of density, temperature, and confinement time to the break-even point. Some key scientists, such as Dr. Robert Hirsch, AEC's former acting director of the controlled-fusion program, are reported exultant about eventual success. Says Hirsch: "Nature is not against us in this work. All we have to do is be careful and do the right things" [9].

The Fusion Plant

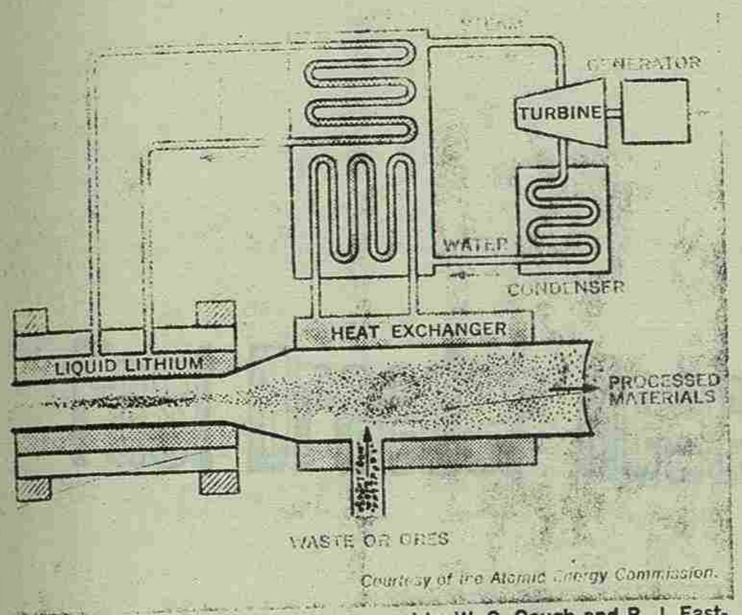
What will a fusion plant look like? There will be no architectural constraints, no need for stacks or reactor-containment buildings. Thus the plant could blend into almost any setting. The physical size has been estimated to be similar to that of a large-reactor generating station, except that extensive additional land area will not be needed for fossil-fuel storage or fission-reactor exclusion area.

What are the principal scientific and engineering problems still to be resolved? First, scientific feasibility of controlled fusion must be demonstrated. This requires scaling-up today's research devices to reactor

Courtesy of Public Service Electric and Gas Co. and Princeton's Plasma Physics Laboratory



Direct energy conversion. This type of conversion would be more suited to those fusion fuel cycles that release most of their energy in the form of charged particles. Conversion could be accomplished [illegible]



Courtesy of the Atomic Energy Commission.

Fusion torch. An idea put forward by W. C. Gough and B. J. Eastlund of the AEC to exploit the ultra-high-temperature plasmas produced by fusion reactors. Some of the energy from these plasmas is here used to vaporize, dissociate, and ionize any solid or liquid material. In its ultimate form the fusion torch can reduce any kind of waste to its constituent atoms for separation.

size to confirm predictions based on current theory and experience. After this, difficult engineering problems will remain, such as: selection of materials resistant to energetic neutron bombardment, thermal stress, and magnetic forces; design of fuel-injection systems; design of a system for removing spent gas [17].

Conclusion

An energy-abundant world will be ushered in against the background of a profound change in life style of both advanced and underdeveloped countries. Because of finite limits to the world's reserves of material resources and to the ability of the earth's ecological system to absorb pollutants safely, the basic economic framework of all countries will be a stationary-state system in which the material economies will be "looped" or circular in place of the present inherently wasteful "linear" materials economies.

In such stationary-state systems, the rate of growth of the gross national product will no longer indicate the state of a country's economic health. Its health will be measured rather by the level of technological sophistication to run a closed materials economy. This will be measured in two ways: (1) the longevity and durability of individual commodities and (2) the technological means to recycle the limited supply of material resources [15].

The "technological means" will be at hand in the form of such devices as the aforementioned "fusion torch" [14] which, with the advent of cheap and abundant power, could become a commercial reality. The ultimate in waste reclamation, this device would employ the ultra-high-density plasma exhausted from a fusion reactor to vaporize, dissociate, and ionize any solid or liquid material placed in its path, in effect, reducing such materials to their constituent atoms, thereby closing the materials loop, the indispensable prerequisite for a stationary-state economy. An old automobile, for example, could be transformed into the iron, lead, and tin from which it was made [14].

Such fusion-torch possibilities are largely untested and many aspects may turn out to be impractical. For the ionization is only the beginning of a possible solution. The hardest part may well turn out to be the problem of "separating the soup into the vegetables," something no one knows how to do in any remotely acceptable (cost-wise) way.

Politically, the effects should be just as profound. Should abundant energy from rocks, the seas, or directly from the radiant energy of the sun materialize, then solutions to the major problem of the "have not" nations—how to improve the living conditions of their peoples above a bare existence level—would finally be at hand. This would greatly enhance the chances for world peace. After all, as has been pointed out with more than a grain of truth, much of what countries do internationally nowadays is intended to forestall future action of neighbors beset with population and raw materials problems [16]. But everyone has "granite, and air, sun, and water." The capability of using these basic elements to achieve abundant energy should be a self-serving contribution of the wealthier nations to their less-fortunate brethren.

Of course, as has been noted elsewhere [15], any effort to rationally utilize an energy-abundant economy will confront the massive economic, social, and political inertia that sustains the present system. Such questions as how to distribute the stock of wealth, including leisure, within a stationary-state economy will face severe scrutiny and arouse intense partisanship.

But this writer, for one, remains hopeful that the world's requirements for energy, intimately tied as they are to such factors as population expansion, economic development, materials depletion, pollution, war, and the organization of human societies, will ultimately be met and the scourge of war and pestilence irrevocably extirpated. Mankind will then enter on the path of its true history, one in which its energies will finally focus on those peaceful pursuits which are the true expression of the human spirit.

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Cooled Fast Breeder Reactor Designs

Part 1—The 300-MW(e) GCFR Demonstration Plant

Various studies of gas-cooled fast breeder reactor (GCFR) systems with both steam and gas turbine cycles have been performed in Europe and the U. S. for about 10 years. Recently, Gulf General Atomic designed a 300-MW(e) demonstration plant under the sponsorship of a group of U. S. utilities and performed safety studies for this system. Here, the authors discuss this plant with its indirect steam cycle and safety features. Next month, Part 2 of this article will be devoted to recent performance studies of large—1000-MW(e)—GCFR plants.

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THERE are approximately 50 gas-cooled power reactors now in operation or under construction around the world, mostly in Europe. The main types are Magnox reactors, using natural uranium metal rods with Magnox cladding, and advanced gas-cooled reactors (AGR) with stainless-steel-clad enriched-uranium-oxide rods. Both types are thermal reactors moderated by graphite and cooled by carbon dioxide; they produce about 15,000 MW(e), which is a large fraction of the world's nuclear electric generating capacity. The next version of the thermal gas-cooled reactor is the high-temperature gas-cooled reactor (HTGR) developed in the U. S. and in Europe; it is also moderated by graphite but it is cooled by helium, and the fuel consists of enriched uranium and thorium carbides in the form of coated particles. This leads to a high exit temperature (~800 C) and a high net cycle efficiency (~40 percent). The first U. S. prototype, the 40-MW(e) HTGR at Peach Bottom, Pa., has been producing power since 1967, and two smaller reactors are operating in England and in West Germany.

A 330-MW(e) HTGR is now under construction at Fort St. Vrain, Colo., and should be in commercial operation in 1972; like all the latest gas-cooled power reactors, the whole nuclear steam supply system is contained within a prestressed concrete reactor vessel (PCRV). Two other HTGRs are also planned for construction in the near future, one in England and the other in Germany, and two 1160-MW(e) HTGRs have been ordered in the U. S.

Fuel utilization in such advanced converters as the HTGR is nearly twice as good as that for "burners," such as light-water reactors (BWR or PWR), but still better utilization of the uranium resources could be obtained with fast breeder reactors where natural or depleted uranium is converted into more fissionable plutonium than is consumed in the reactor itself. About 50 percent of the U-238 in a fast breeder reactor (FBR) could be converted into fissile plutonium in a

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Based on a paper contributed by the ASME Nuclear Engineering Division. This work was supported in part by the member utility companies participating with Gulf General Atomic in the GCFR development program.

30-year period. The incentive for development of fast breeders is not only the need to utilize existing depleted uranium and anticipated plutonium stock piles and to conserve existing uranium resources, but also to achieve high cycle efficiency (~40 percent) and low fuel cycle costs (<1 mill/kwh).

Although the first electric power ever produced by a nuclear reactor came out of the first fast breeder [0.2 MW(e) in EBR-I in 1951], it will have been 20 years before the first sizable fast breeder demonstration plant will be operative (the BN 350 in the USSR). Two other demonstration plants are scheduled to start up in 1972 and 1973 in England and France, respectively. The first demonstration plant in the U. S. will probably not be operating before 1978. All of these fast reactors are cooled by a liquid metal.

Four coolants have been considered for fast breeder reactors: liquid metals (e.g., Na or NaK), steam, helium, and carbon dioxide. Sodium has several advantages as a fast-reactor coolant, such as good heat-transfer characteristics at low pressure and high temperature and good emergency cooling characteristics, but it is an opaque fluid that can boil or freeze, is active chemically, and becomes radioactive in the reactor. Therefore, a great deal of effort is needed to develop reliable components such as steam generators. An intermediate liquid-metal heat-transfer circuit is required to avoid the possibility of steam entering the primary circuit and reacting with the radioactive sodium. The metallurgical and safety problems that would arise from the use of steam as a fast-reactor coolant are much less severe with helium and carbon dioxide. Helium is chemically inert, does not become radioactive, does not change phase, is transparent, and does not degrade the neutron spectrum, thus leading to a high conversion ratio and a negligible void reactivity coefficient. Heat-transfer characteristics of helium under typical fast-reactor operating conditions are not much different from those of sodium [1],[2] especially since the surface heat-transfer coefficient can be significantly increased (≥ 2) by artificial roughening of the fuel-rod surface. Although pressurization is required (70 to 85 atm), the fact that the whole primary system is totally enclosed within a PCRV makes a rapid depressurization accident highly improbable. The combination of a pressurized secondary containment and several independent main and auxiliary cooling loops helps to alleviate emergency cooling problems since natural convection in helium is usually insufficient [2]. Carbon dioxide has properties similar to those of helium but it could create corrosion problems.

Several types of gas-cooled fast breeder reactors (GCFR) have been proposed in the past decade but only two are being seriously considered: conservative designs using stainless-steel-clad, mixed plutonium and uranium oxide fuel rods cooled by helium, with an indirect steam cycle; and advanced designs with vanadium-clad rods or ceramic-clad, mixed plutonium and uranium carbide-coated particle fuel, with a direct helium gas turbine cycle. Most of the efforts spent on design development in Europe and in the U. S. have been on the first type of GCFR, which is based on LMFBR fuel and physics development and on HTGR technology, such as the PCRV, circulator, and steam generator. This deliberate choice should lead to development of a GCFR within a time scale comparable to that of the LMFBR, while maintaining a capability for even further substantive improvements, such as higher-temperature cladding, carbide fuel, and direct cycle. As an example of commonality with LMFBR fuel, the GCFR fuel rods are collectively vented to a manifold so as to equilibrate the pressure on either side of the cladding, thus removing the effect of high helium coolant pressure.

300-MW(e) GCFR Demonstration Plant Design

The principal design objective of the GCFR demonstration plant is to demonstrate reactor performance and operational characteristics typical of large commercial plants. The nominal power level of 300 MW(e) was chosen to demonstrate performance of full-scale components, such as fuel elements, helium circulators, and steam generators, and also to demonstrate the neutronic and fuel-cycle characteristics under conditions of irradiation that correspond to those of a large commercial GCFR power plant.

The design is based on the maximum utilization of fuel technology under current development in the U. S. and in Europe on the LMFBR program, and on the continuing development of the component technology that forms the basis of the 40-MW(e) prototype HTGR at Peach Bottom and the 330-MW(e) HTGR Fort St. Vrain power plant.

Conservative design bases have been used throughout, and a breeding ratio of 1.33, or 1.5 with 3 rows of radial blanket, is obtained under these conditions. This is largely due to the desirable properties of helium as a fast-reactor coolant. The helium has a small neutronic interaction, thereby leading to a good neutron economy and avoiding any possible reactivity effects; furthermore, the coolant does not become radioactive. Because the design assumptions are conservative, there is considerable performance growth potential inherent in the GCFR concept.

The reactor, the helium primary coolant system, and the steam generators are enclosed in a PCRV located in a reactor building that functions as a secondary containment structure and also contains the fuel-handling area and the reactor plant process and service systems. The fuel storage pool is in a fuel service building adjacent to the reactor building and is connected to it through a loading port. The steel-lined PCRV is prestressed after completion of the concrete construction by a system of longitudinal and circumferential steel tendons.

Containment of the entire primary system in a PCRV is a fundamental aspect of the GCFR design, which makes a rapid loss of coolant through depressurization, caused either by failure of primary coolant ducts or by vessel failure, not credible. This characteristic limits loss-of-coolant safety and design problems to the penetration closures. For these, flow-restriction means are designed into each large penetration, structurally independent of the primary closure, to limit the maximum rate of depressurization into the secondary containment.

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[2] Numbers in brackets designate References at end of article.

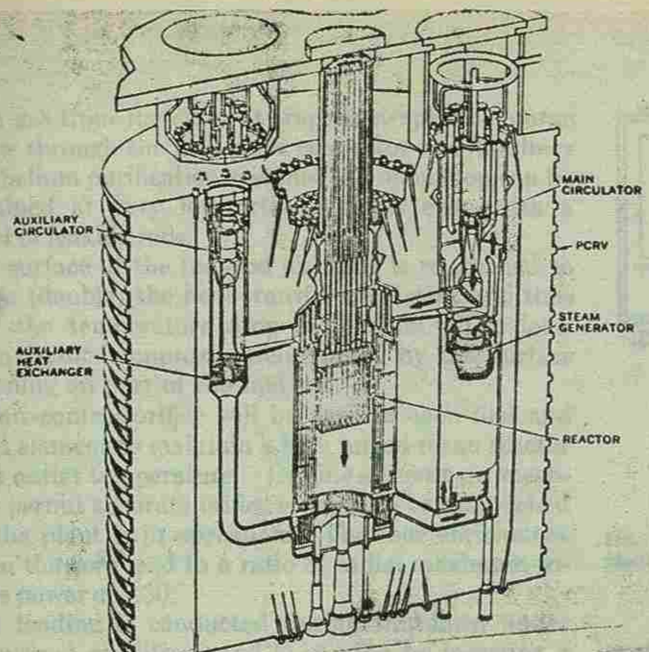


Fig. 1 300-MW(e) GCFR demonstration plant.

The primary coolant system contains three main loops, each with independent boilers and circulators, Fig. 1 (right), and three auxiliary loops, Fig. 1 (left), each with its own circulator and heat-removal system. The auxiliary loops are used for long-term shutdown cooling and as backup for the main loops. The steam generators and their associated circulators are housed in vertical cavities in the walls of the prestressed concrete vessel surrounding the reactor core. The helium coolant, at a pressure of about 1250 psia, flows downward through the core where it is heated to a temperature of 1007 F. The flow is also downward across the tube banks of the helical-coiled once-through steam generators to accommodate the use of upflow boiling in the generators.

The reactor outlet gas flows up through a central hole in the tube bundles, down through the resuperheater and steam generator, and up again around the boiler shells to top-mounted circulators, from which it is discharged to the reactor top plenum at a temperature of 593 F.

The three main coolant circulators each have a single-stage axial blower driven by a series steam turbine in the high-pressure steam line. Thus, a mechanically simple and very compact power source provides the necessary large circulator power (22,300 hp each), making each main loop as self-contained and independent of the others as possible. In addition, afterheat initially provides power for its own removal. Circulation for auxiliary cooling is provided by centrifugal circulators, each driven by a 500-hp electric motor.

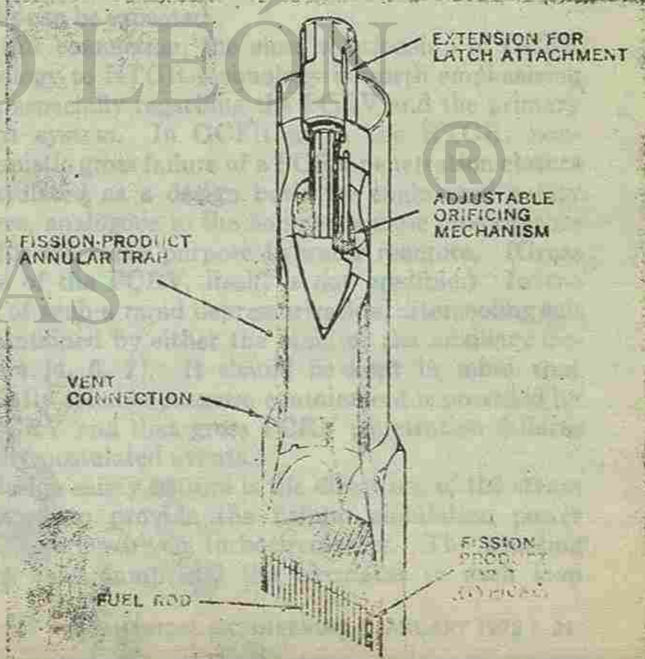
The reactor assembly contains 118 hexagonal fuel and 93 blanket elements. The elements, which are 10 ft in length and 6½ in. across flats, are supported from a top-mounted grid plate. They are clamped to the grid plate solely at their cold ends. Irradiation-induced metal swelling will be accommodated in the design of the core by the provision of a 0.25-in. gap between adjacent elements in the active core region. Bowing due to differential swelling will be minimized by rotation of elements at partial refueling intervals. The fuel-element-to-grid-plate clamps and variable orifices of each element are actuated by external mechanisms that have drive shafts above each element through the top access plug.

Each standard fuel element contains 271 fuel rods. The fuel rods consist of annular $(Pu\text{–}U)O_2$ pellets within a 316 stainless steel cladding about 20 mil thick. Upper and lower axial blankets are contained in the ends of the fuel rods and consist of depleted UO_2 pellets. The blanket elements each have 127 rods of larger diameter that contain depleted UO_2 pellets.

The fuel-rod design conditions include a maximum temperature of 700 C (1292 F) at mid-thickness of the fuel cladding (including hot-spot factors), a cladding thickness ratio of 1.15, and a "smeared" fuel density within the cladding of 80 percent of theoretical density. The maximum design burnup was chosen to be 100,000 Mwd/tonne, and the maximum linear rating (with 10 percent overpower) is 13.8 kw/ft. These design parameters were selected after evaluation of existing irradiation data and are within the range now planned to be tested in the AEC's Fast Flux Test Facility (FFTF) and in the LMFBR demonstration plant programs.

The fuel rods are vented to equalize internal gas pressure to that of the reactor coolant outside the rod. This eliminates the need for a rod designed to prevent cladding creep collapse and will provide a demonstrated basis for reducing cladding thickness in later designs in order to increase plutonium production through better conversion ratio. Radiation monitors on the vent lines leading to the helium purification system provide means for detecting any leaks in the fuel rods. The fuel elements contain charcoal-filled fission-product delay traps in each of the fuel rods and also a single second-stage trap in the inlet end of the fuel element, as shown in Fig. 2. These traps are well cooled and delay the passage of the volatile and gaseous fission products long enough to minimize subsequent heat release. The arrangement permits adequate trapping for the life of the element even with several leaking rods in an element. Helium entering such a leak has, of course, no effect on reactor operation, and since the flow of vent

Fig. 2 Section through GCFR fuel-element inlet.



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system gas from the element traps is swept by a purge gas flow through the grid plate connector into the lines to the helium purification systems, the main loop can be maintained at very low activity levels even with a number of leaking rods.

The surface of the fuel-rod cladding is roughened to increase (double) the heat-transfer coefficient and thus reduce the temperature drop in the film. The local friction factor is approximately tripled by this surface roughening on part of the fuel rod.

A flow-control orifice will be used in each fuel and blanket element to maintain a high mixed-mean reactor coolant outlet temperature. On-line adjustment mechanisms permit accurate orifice settings to be established while the plant is in operation. The four enrichment zones in the core lead to a ratio of radial maximum-to-average power of 1.30.

Core loading is conducted during shutdown under depressurized conditions and is effected by inserting a fuel-transfer machine through the bottom of the PCRV. This machine lowers and traverses fuel in the vacant space below the core to a single exit port leading to a transporting cask beneath the vessel structure [3]. Partial core reloading will occur at approximately annual intervals, one-third of the core being changed every year.

Reactivity control is by 27 rods in the control fuel elements, which have central channels to accommodate the rods. The control-rod drives are located above the reactor. Normal operation of the reactor, requiring a total reactivity swing of \$17, including a minimum \$3 shutdown margin at all times, is provided by 21 control rods, each of which is limited for safety reasons to \$0.85 worth. The six shutdown rods, each having a value of \$1.60, form a backup system capable of independently shutting down the reactor from any anticipated operating conditions.

Protection of the PCRV liner and ducts from neutron irradiation is provided by thermal shielding. Around the core this shielding takes the form of a replaceable inner layer of steel blocks surrounded by an annular region consisting of steel cylinders containing graphite. Cooling of the radial shielding is by a small bypass from the inlet helium.

The concrete plugs above the steam generators incorporate large central holes for circulator removal and smaller surrounding holes for steam pipes. Steam generator tube plugging can be done externally; the main penetration closure is removed only for complete removal of the steam generators.

The GCFR steam cycle is noteworthy in that resuperheaters are used following the circulator turbines. This, in effect, confers most of the advantages of normal reheat and provides steam dry enough to avoid the necessity for moisture separation in the main turbine.

Fig. 3 shows a simplified heat-balance diagram for the demonstration plant. In each main loop, hot helium (at 1007 F) out of the reactor first reheats the steam in a resuperheater, after which the helium flows into the superheater, evaporator, and economizer sections of the steam generator. It then passes through a helium circulator before it is returned to the reactor at 593 F (311 C). The main steam flow goes through a blower turbine, is returned to the steam generator to be resuperheated to 925 F, and then goes to the main turbine. The net cycle efficiency of 37.6 percent leads to a net electric power of 311 MW(e) for 875 F, 2900-psi steam conditions at the superheater outlet. The steam conditions at the main turbine throttle are 922 F and 1223 psia. Further design data on the demonstration plant are given in Table 1.

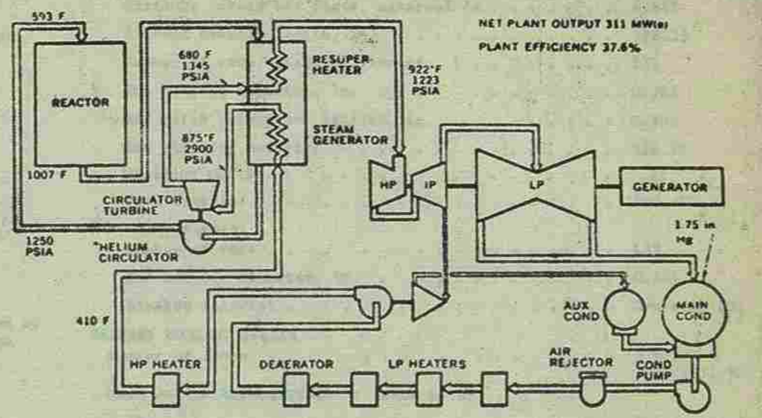

Fig. 3 Simplified heat-balance diagram for GCFR demonstration plant.

Safety Considerations

A major effort has been placed on safety studies [4] and these have continued to confirm the advantages of helium as a reactor coolant. There are no possible change-of-phase problems nor are there any cladding–coolant, fuel–coolant, or steam–coolant reactions to design for; engineering for overall system safety is, therefore, eased.

An important design safety feature of the GCFR is the enclosure of the entire primary coolant system in the PCRV, thereby eliminating primary coolant ducts. Because of the conservative design bases, the highly redundant prestressing system, and the predictable, noncatastrophic failure modes, PCRVs are considered by many to have desirable safety features [5]. As design, construction, and operational experience accumulates with the 20 PCRVs both in this country and in Europe, wider understanding and acceptance of PCRVs can be expected.

In this connection, the close relationship of GCFR technology to HTGR technology is worth emphasizing again, especially regarding the PCRV and the primary coolant system. In GCFR as in the HTGR, nonmechanistic gross failure of a PCRV penetration closure is postulated as a design basis for engineered safety features, analogous to the nonmechanistic pipe rupture used for the same purpose in water reactors. (Gross failure of the PCRV, itself, is not credible.) In the event of such a rapid depressurization, aftercooling can be maintained by either the main or the auxiliary circulators [4, 6, 7]. It should be kept in mind that inherently reliable pressure containment is provided by the PCRV and that gross PCRV penetration failures are only postulated events.

A design safety feature is the direct use of the steam generated to provide the helium circulation power through series-driven turbocirculators. The coupling of the heat dump and the circulator in each loop

TABLE 1 300-MW(e) GCFR Demonstration Plant Data Summary

GENERAL	
Average breeding ratio	1.33
Maximum fuel burnup, MWd/Te heavy metal	100,000
Net electrical power, MW(e)	311
Plant efficiency, %	37.6
Steam conditions at main turbine	
Throttle pressure, psia	1223
Throttle temperature, °F	922
Condenser pressure, in Hg, absolute	1.75
Reactor coolant	Helium
Reactor coolant pressure, psia	1250
Reactor vessel and primary containment	PCRV
PCRV dimensions, ft	84 diam by 17 high
REACTOR	
Reactor geometry	
Core height, in.	39.2
Core length-to-diameter ratio	0.5
Axial blanket length, each end, in.	17.7
Reactor subassemblies	
Standard fuel elements	91
Control fuel elements	27
Radial blanket elements	93
Core volume fractions, %	
Fuel	30.1
Helium coolant	44.6
Cladding	10.0
Structure	6.0
Gaps (box interspace, control-rod channel)	9.3
Reactor heat transfer	
Helium temperatures	
Reactor inlet, °F (°C)	593 (312)
Mixed mean outlet, °F (°C)	1007 (541)
Average power density, kWt/liter of core	238
Maximum linear rating (10% overpower), kW/ft	13.8
Hot-spot cladding temperature, °F (°C)	1290 (700)
Radial maximum-to-average power	1.30
Axial maximum-to-average power ratio	1.20
Rod surface roughening	
Fraction of active core length roughened, %	75
Roughening heat-transfer multiplier	2
Roughening friction-factor multiplier	3
Maximum heat flux, Btu/(hr)(ft^2)	520,000
Core and axial blanket power fraction, %	95.55
Radial blanket power fraction, %	4.45
Nuclear characteristics (midcycle)	
Fissile core loading (Pu), kg	1320
Average fast neutron flux (E > 0.1 MeV), n/cm^2-sec	2.2 x 1
Reactor rating, MW(t)/kg fissile	0.605
Doppler constant, TdK/dT (T in °K)	-0.0032
Fuel lifetime, full-power days	750
Partial refueling cycle, yr	1
Fuel element	
Distance across hex flats, external in.	6.642
Element overall length, in.	118.25
Number of rods, standard element	271
Rod outside diameter, in.	0.282
Rod pitch triangular lattice, in.	0.386
Rod cladding material	316 SS
Cladding OD/ID	1.15
Fuel material	PuO_2-UO_2
Blanket element	
Number of rods	127
Rod outside diameter, in.	0.464
Blanket material	Depleted UO_2
PRIMARY COOLANT SYSTEM	
Number of loops	3 main, 3 auxiliary
Main helium turbocirculator (each of 3)	
Type	Single-stage axial
Drive	Steam turbine
Pressure rise, psi	60
Brake horsepower (per circulator)	22,300
Steam generators (each of 3)	
Type	Helical once-through
Heat duty, Btu/hr	8.45 x 10^8
Surface area, ft^2	33,400
Feedwater temperature, °F	412
Steam outlet temperature, °F	875
Steam pressure, psi	2900
Resuperheater	
Type	Helical
Heat duty, Btu/hr	1.47 x 10^8
Surface area, ft^2	3600
Steam temperature out, °F	925
Auxiliary heat exchanger (each of 3)	
Type	Helical, water cooled
Heat duty, Btu/hr	56.4 x 10^6
Surface area, ft^2	1180
Auxiliary circulator (each of 3)	
Type	Single-stage, centrifugal
Drive	Electric motor
Brake horsepower (per circulator)	500
TURBINE GENERATOR	
Type	TC6F-23
Speed, rpm	3600
Gross electrical output, MW	316
SECONDARY CONTAINMENT	
Type	Reinforced concrete
Inside diameter, ft	124
Height, ft	176
Atmosphere	Air
Equilibrium pressure, atm, absolute	2

increases the reliability of cooling. The GCFR turbocirculators are similar in concept and in many details to the HTGR turbocirculators.

The primary system is designed to operate with a limited amount of steam inleakage and the effect on reactivity is negative.

The use of pressure-equalized fuel rods also has important safety benefits. Most important is the elimination of fuel failure modes due to cladding collapse from high external pressure (at start of irradiation) or due to cladding deformation or rupture from internal fission-gas pressure (later during irradiation).

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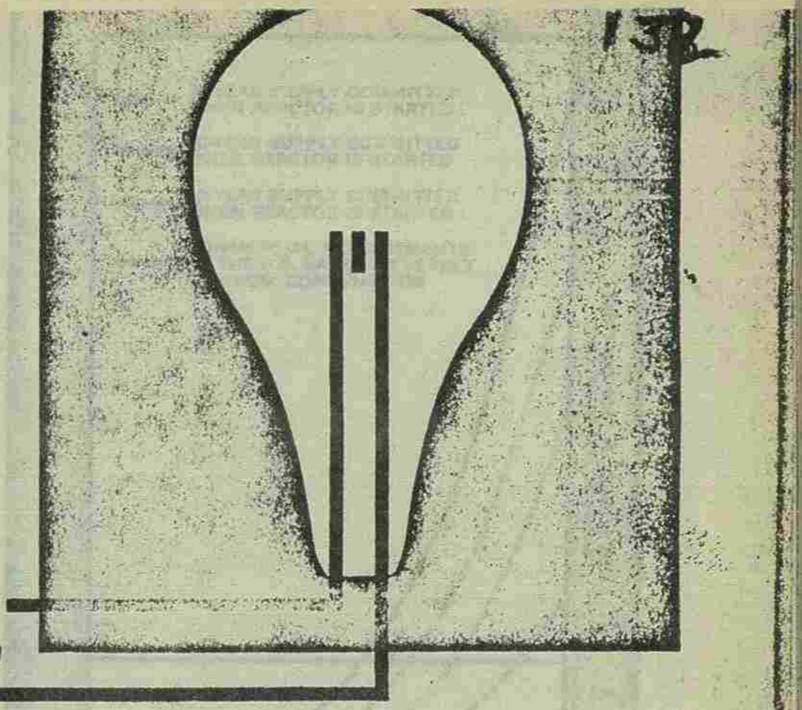
MHD CENTRAL POWER: a status report



MHD offers unmatched advantages: high thermal efficiency (50 to 60 percent), no air pollution other than CO_2, and no radioactive waste. And it may shrink the nation's power bill by $40 billion to $130 billion. Other countries, particularly the Soviet Union, are investing large efforts in MHD. We are dragging our feet. In light of the fact that our uranium supply is running out and the breeder reactor is still a question mark, we must reexamine our priorities.

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On June 4, 1971, President Nixon released a message to the Congress concerning the energy crisis. The main thought of the message was to ask for more money for the nuclear breeder reactor. It is obvious from the timetable given, which sets a goal of 1980 for demonstration of the breeder reactor, that such devices will not be available in time to alleviate the impending uranium shortage discussed in this paper. The president, at the same time, argued the necessity of a more-balanced research and development attack on the energy problem and requested an increase in funds for the coal-gasification problem. Although this is a step in the right direction, it does not go far enough in anticipating the role of fossil fuel during the next 50 years in the U. S.

Some important factors were neglected, particularly the promise of MHD central power, both technologically and economically. The FY 72 proposed budget goes somewhat further in recommending increased expenditures for coal gasification and includes $3 million to begin an MHD central-power program. This $3-million amount is significant but inadequate when compared to the national programs conducted in other countries.

An Old Principle

Magnetohydrodynamic power generation is achieved when an easily ionized metal, such as potassium or cesium, is introduced into high-temperature combustion gas which is expanded to high velocity through a nozzle and then directed into a magnetic field with properly arranged electrodes and external circuit.

In this situation, a moving conductor cuts magnetic-field lines and a useful emf is generated. Although this kind of electrical configuration was described by Faraday over 100 years ago and was one of the first generator configurations invented, the problems associated with high temperature have prevented its application to combustion-gas plasmas until recently. Through the use of current high-temperature technology and some 10 years of research and development in MHD, the state of the art has reached the point such that 10 more years of work can produce large power plants in the 2000-MW range for practical use. The impetus for developing such plants lies in their high thermal efficiency, between 50 and 60 percent as compared to 40 percent for conventional fossil fuel and 32 percent for nuclear power plants. This makes MHD-type steam plants attractive from the standpoint of economics, thermal pollution, and air pollution.

Within the past two years a whole new technical situation has arisen within the context of a changing social climate, so that the current status of MHD is quite different from that set forth in the August, 1969, issue of Mechanical Engineering [5].[2] No longer is the future of MHD technology or any other tech-

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[2] Numbers in brackets designate References at end of article.

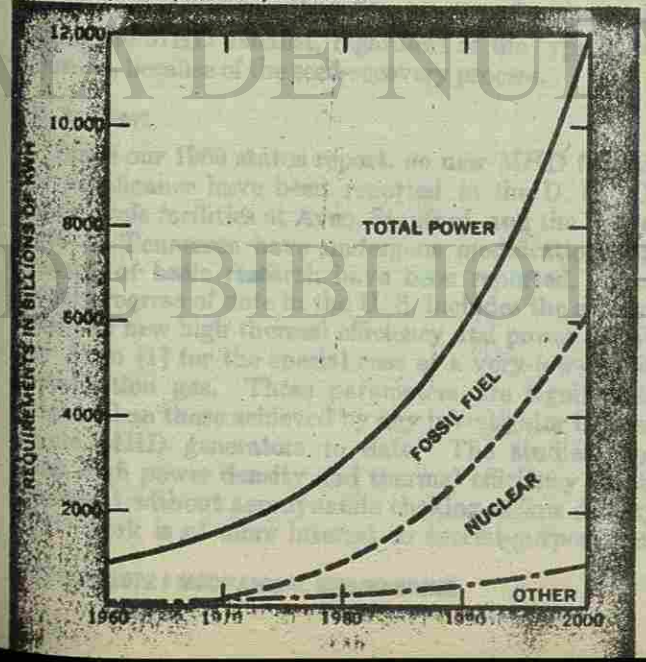
nology a simple estimate of technical feasibility and economic benefit. The public acceptance of power plants, the future power-demand curves, the cost of power-plant construction, and the effect of all these factors on power sources other than MHD must be considered in order to adequately describe the status of the technology. The posture of the federal government and its organization with respect to central power will profoundly affect the future of any technology and thus needs to be examined as well.

It is now, therefore, a good time to review the status of MHD central power. A good place to start is at the international meeting concerning MHD power generation held in Munich, Germany, in April, 1971. Of particular interest was the announcement of an operating Soviet MHD experimental facility, U-25. Extensive Soviet experiments on long-duration preheaters, MHD channels, and other components have been performed. Smaller, but significant, experiments on central power components have also been constructed in Japan.

Future of MHD

The prime question should be: Is the expenditure of some $282 million necessary to acquire MHD power-generation technology a reasonable technical risk in which the people of the U. S. can expect a large return in the future? If this question can be answered in the affirmative, then the discussion will turn to the acceptability of MHD power generation from the standpoint of safety to the public, pollution of the environment, and other peripheral economic effects to be reasonably expected. Fig. 1 shows a version of the traditional power-demand curve for the U. S. until the year 2000. It is possible to avoid answering questions concerning the competition between MHD fossil-fuel plants and a system of nuclear power plants by merely calling attention to the fact that nuclear plants by their very nature must be base-load plants and that the rest of the power needs might be satisfied largely by MHD power plants. Thus, some 30 percent of the power plants might be MHD plants with the rest nuclear. Such a power system is not necessarily the optimum one for the country, however. Leaving aside for a moment the question of the acceptance of the conventional nuclear plant and the breeders by the public, it is worthwhile to take a look at the economics of the nuclear system as compared to a system where fossil-fuel MHD plants take over a large portion of the power production.

Fig. 1 Projected power requirements.



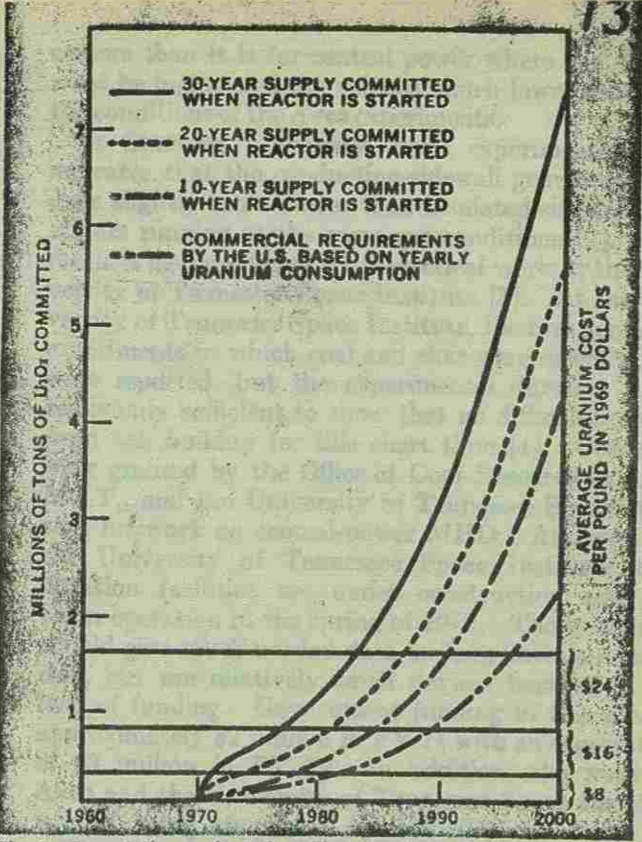


Fig. 2 Cumulative projected uranium requirements.

The lower curve in Fig. 2 shows the projected cost of uranium in 1969 dollars if nuclear reactors are put into service as estimated from the curve in Fig. 1. This is not a realistic cost curve because it assumes that uranium is bought at the time it is consumed, which is not the usual practice. If we assume that the utilities will follow the usual custom of obtaining contracts for nuclear fuel for all (30 years) or a large part of the lifetime of the reactors, our uranium reserve would be committed to fueling reactors as they are built. The effect is shown in Fig. 2 for 10, 20, and 30 years of uranium supply committed to the reactor when it is built. One sees that the reactors will be priced out of competition after 1985, because the 1969 price of $6.50/lb will have increased by a factor of three to four for new reactors. The standard answer from the nuclear establishment to all who point out this obvious future uranium shortage is that additional exploration will turn up the required uranium supply. However, anyone familiar with the current oil and gas situation will have grave reservations concerning the assumption that mineral resources can always be found when needed.

Another answer—this one from the Atomic Energy Commission—is that breeder reactors, when installed, will alleviate the uranium supply shortage. But even optimistic estimates of a fuel doubling time of 10 years in the breeder leads to a prediction that it would require 30 years to fully install a breeder system that

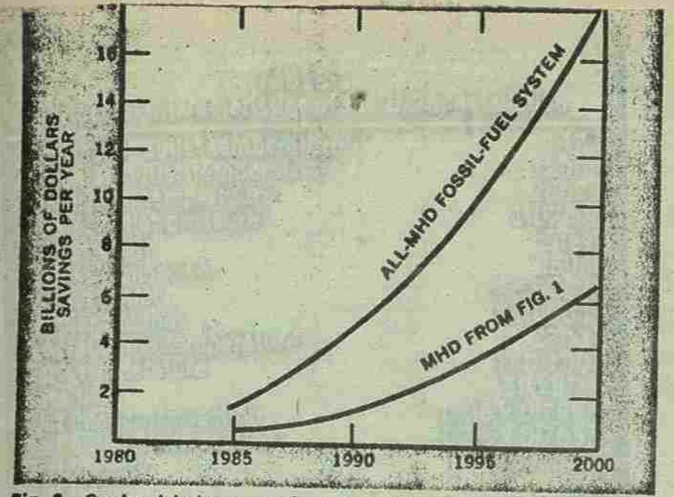


Fig. 3 Contrast between savings brought about by MHD from the fossil-fuel system predicted in Fig. 1 with an all-fossil-fuel system for plants constructed after 1985.

would supply most of the nation's power needs. One must add to this 30 years the fact that it will probably take at least 10 years to site and build the first generation of breeders and that the breeder, of course, is not developed as yet and may require 10 to 15 years development time. We finally come up with the fact that it will be 50 years from now before the breeder can fully supply the uranium required for a completely nuclear central power system in the U. S. It is obvious that breeder reactors will not be on the line in appreciable numbers before 1995, and that long before this time the cost of uranium will have risen by a factor of three or four.

Reduced Power Bill

The yearly savings in the nation's power bill, if MHD fossil-fuel plants were installed beginning in 1985 instead of ordinary fossil-fuel plants, are shown in Fig. 3. The upper curve represents the savings to be realized if fossil fuel takes over completely from nuclear fuel in 1985, and the lower curve indicates the savings if the split between nuclear and fossil-fuel power generation is as shown from the curves in Fig. 1. If MHD central power plants of 55 percent efficiency are developed, one would expect the savings in the power bill to lie somewhere between these two curves. The competition might very well be effective in lowering the cost of nuclear power as well. It is assumed in making these cost estimates that SO_2 is virtually eliminated from the MHD exhaust, regardless of the type of coal burned, because of the seed-recovery process.

U. S. Effort

Since our 1969 status report, no new MHD facilities of significance have been reported in the U. S. Old open-cycle facilities at Avco, Stanford, and the University of Tennessee have undergone modifications, and results of basic research have been reported. Technical progress of note in the U. S. includes the achievement of new high thermal efficiency and power density by Avco [1] for the special case of a very-low-density combustion gas. These parameters are significantly higher than those achieved by any investigator in open-cycle MHD generators to date. The studies show that high power density and thermal efficiency can be obtained without aerodynamic choking at low density. This work is of more interest to special-purpose generators than it is for central power where the density must be higher and the velocity much lower than with the conditions of the Avco experiments.

At Stanford University, basic experimental work indicates that the conducting-sidewall generators produce slightly more power than insulated-sidewall generators running at the same gas conditions [2]. This result is also predicted by theoretical work at the University of Tennessee Space Institute [3]. At the University of Tennessee Space Institute, the first generator experiments in which coal and char were directly fired were reported, but the experimental duration of 12 sec is only sufficient to show that no difficulties occur from ash buildup for this short time [4]. Contracts were granted by the Office of Coal Research to Avco, M.I.T., and the University of Tennessee Space Institute for work on central-power MHD. At Avco and the University of Tennessee Space Institute long-duration facilities are under construction and will begin operation in the spring of 1972. These facilities should give much-needed data on long-duration operation, but are relatively small devices because of the lack of funding. Government funding in this area is approximately $2 million in FY 71 with an expectation of $3 million in FY 72. In addition, the work at Avco and the University of Tennessee Space Institute is also being supported by contributions from the utilities.

International Status

By far the most spectacular results were announced by the delegation of the Soviet Union when it was stated that an announcement had been made in Moscow at the 24th Party Conference in March, 1971, that a new kind of power plant was in operation on the Moscow power network. This plant is the U-25 whose prospective design was described in MECHANICAL ENGINEERING's August, 1969, issue [5–8]. Conjecture in the U. S. had commonly speculated that this plant would begin operation somewhere around November, 1971, so it appears to be ahead of our original estimates. The plant is complete, except for the steam turbine of the bottoming unit which would be of no importance in the experimental plant. A new set of specifications for this plant was presented as shown in Table 1. The author and several other people from the U. S. had an opportunity to inspect this plant in conjunction with the Joint IAEA/ENEA International MHD Liaison Group meeting in Moscow in December of 1971.

The plant's exterior air preheaters consist presently of aluminum oxide, and are heated by natural gas and then used to heat the incoming air. Such heaters will be periodically cycled to provide a continuous flow of air at 1200 C. Such preheat is necessary in the MHD cycle in order to make the combustion products conducting. In the U-25 additional temperature is gained through the addition of a small amount of pure oxygen preheated at 1200 C to the air. The preheaters have been in operation for some time, though it is not completely clear for how long they have been operated. Others at the High Temperature Institute have been cycled for 8000 hr. Fig. 4 shows the MHD magnet enclosing the MHD channel and the accompanying diffuser. The combustion chamber is drastically smaller than the combustion chambers used with con-

TABLE 1
Principal Characteristics of the U-25 Installation

Compressor outlet temperature	147 C
Air-heater outlet temperature	1200 C
Combustion temperature	2800 C
General outlet pressure	1.07 atm
Field strength	2 tesla
MHD electric power	25 MW
Turbine power	86,000 kw
Net plant output	81,000 kw
General outlet temperature	2300 C
Stack temperature	150-180 C
Mass flow	50 kg/sec
Duct inlet cross section	0.38 x 0.766 m
Duct outlet cross section	0.38 x 0.783 m
Duct velocity	850 m/sec
Duct length	5 m
Compressor power	5.6 MW
Auxiliaries power	5000 kw
O_2 plant power	16,000 kw
Magnet power	2.8 MW
Plant efficiency	30 percent
Thermic power	250 MW
Central-power steam	50 MW
Total power	75 MW
Combustible	natural gas
Combustant	enriched oxygen
Temperature of preheated enriched oxygen	1200 C
Seed	potassium
Combustion-gas supply	50 kg/sec
Entrance pressure	2.75 atm
Entrance velocity	850 m/sec
Steam pressure	100 atm
Temperature of the superheater	540 C
Feed-water temperature	150 C

ventional power plants of the same size, because of the high temperature and pressure. Fig. 5 indicates somewhat the size of the experimental installation, showing the generator diffuser, downstream heat exchanger, and exhaust-cleanup and seed-recovery tower. Their seed-recovery process is quite successful, as the Moscow group claims 99.9 percent seed recovery. Other technical triumphs in this program include successful operation of boiler tubes for long periods of time in a potassium-seed combustion gas.

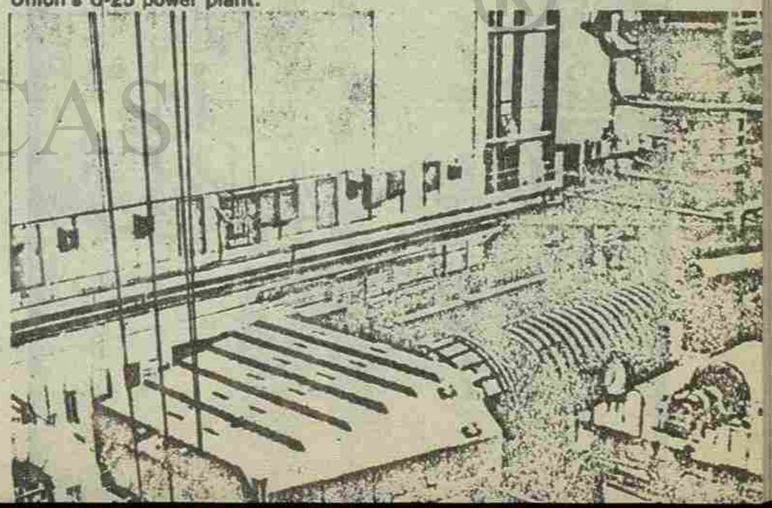
Soviet Effort: $200-million Bread Board. It is interesting to speculate on the rationale behind this approach by the High Temperature Institute to develop MHD central-power technology. The approach is all the more interesting since no large-scale development in nonnuclear power plants has been undertaken before. In general, rather than taking a revolutionary approach, power technology has crept slowly year by year up to higher powers (13 MW) at slightly increasing efficiency. In Professor Scheindlin's method a gigantic experimental bread board has been constructed. The power-plant components are widely separated and housed in a large building devised so that experimental changes can be made with ease. Because of the problem of radioactivity, it is not possible to develop nuclear power along these lines, but MHD suffers from no such limitations and the bread-board approach will give the Soviet Union an optimum experimental program. For example, the question most frequently asked is, What is the optimum channel design for the MHD generator, and what is its capability of endurance? The U-25 is so designed that a number of trial channels can be placed within its magnet and tried in succession. We have seen pictures of such channel construction and believe that a number already exist constructed with cold walls, hot walls, and intermediate temperatures. The only design that we have examined in detail is a water-cooled channel designed for Faraday operation containing many water-cooled copper hemispherical electrodes.

One photograph that we have seen of these devices was the corner of such a channel shown in a motion picture. It appeared to be a steep-diagonal-wall design with relatively large insulator spacing. We expect that in addition to the diagonal-wall electrical design, Faraday and Hall channels will be tried as well, so that in the near future the High Temperature Institute will have information on which channel works best. Not only is the MHD channel removable in this setup, but other components are as well. We expect that the conventional magnet will be replaced by a superconducting magnet at some time. We have been told that the seed-removal and exhaust-cleanup device has been used at some other location. We were also informed that the performance of the preheaters was not satisfactory, and some improvements will be made in these devices.

We have been told that there are 1000 people at work on this MHD project alone, and we believe that the project itself is skillfully and intelligently organized so that the Soviet Union will acquire the necessary technology for central power in a short period of time at an optimum cost. Questions of endurance and electrical efficiency will be solved in good time, and the High Temperature Institute should be congratulated on its ability to put such a plant in operation so soon. In the U. S., because of cost limitation, we are at least five years away from a plant of this type. The hardware not including design cost is valued at $50 million. The very large auxiliary oxygen plant would add a substantial amount to this.

West German MHD Program. The West Germany open-cycle MHD program is divided into two parts. One group is at the Max Planck Institut für Plasmaphysik in Garching near Munich, with its work centered around generators designed for operation of times less than 1 hr, and is cooperating with the MAN Corp. of Munich [9]. Magnetohydrodynamic generators have very quick starting characteristics, and without special effort can be brought to full power in less than 1 sec. Some of the smaller utility companies in West Germany

Fig. 4 MHD magnet, channel, and generator diffuser of the Soviet Union's U-25 power plant.



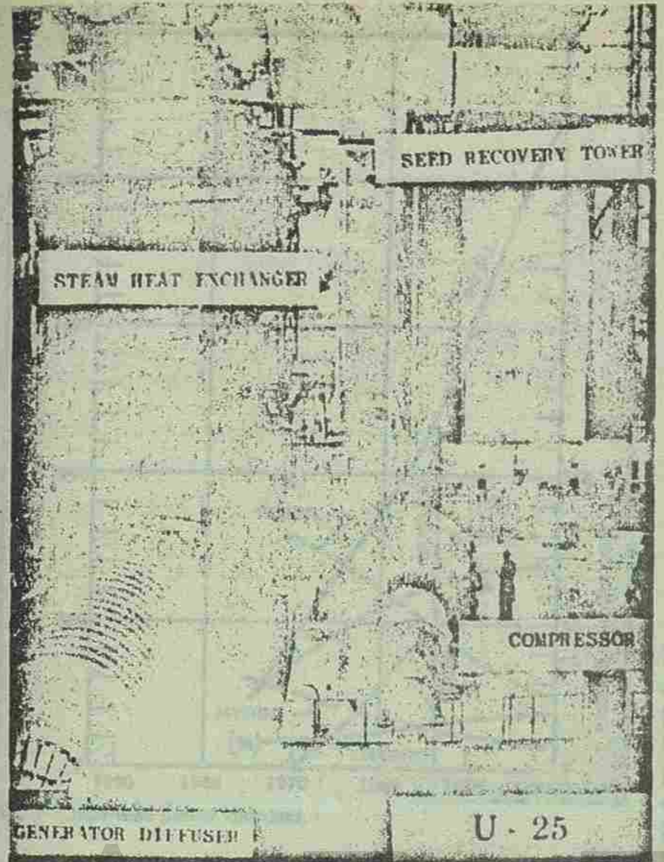


Fig. 5 Generator diffuser, downstream heat exchanger, and exhaust-cleanup and seed-recovery tower of the U-25 power plant.

are very interested in generators having this characteristic, as they are now having to buy peak-load power from larger utilities for very short times at very high rates. It is also thought by the group in Garching that such generators will have utility in fusion power plants, especially in the development program for such devices.

The second effort is being conducted on MHD generators with operating times greater than 1 hr [10]. This effort is being carried on by cooperation between the Institut für Technische Physik in Julich and the Forschungsinstitut des Steinkohlenbergbauvereins, Bergbau-Forschung GmbH at Essen. Experiments up to 20 hr have been run with a small MHD channel in Julich. In Essen, work is underway on a unique process for inexpensive enrichment of air with oxygen. This air-enrichment process could have a profound effect on MHD generator systems if it develops as currently projected from initial work.

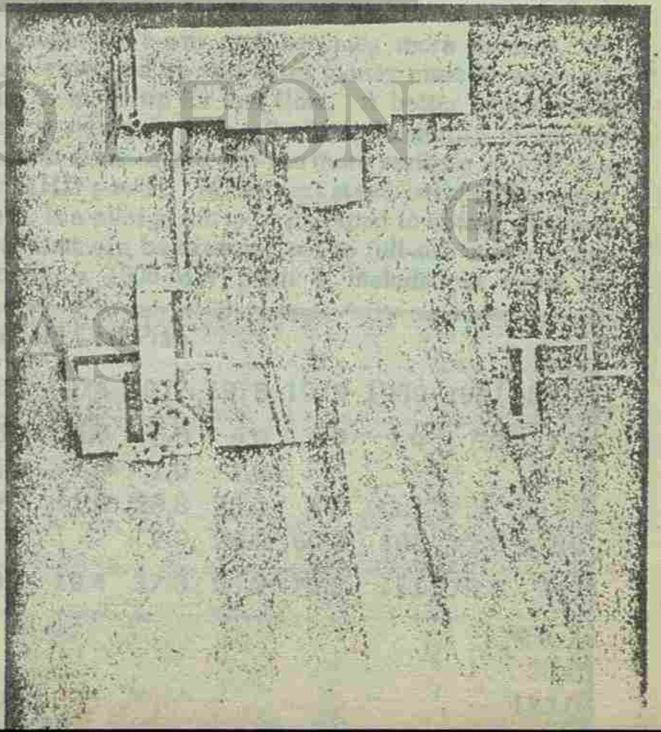
In Garching, the first very-high-magnetic-field MHD generator ever built is being tested with magnetic fields up to 50 kg (Fig. 6). This work is yielding very important data in a magnetic-field range that cannot be reached by other investigators. The MHD channel is of diagonal design at a 45-deg angle similar to those that have been investigated previously [4, 11, 12]. As it is projected that both peaking plants and central power plants will operate with superconducting magnets in the range of 50 kg, the results of the Garching experiments are of great interest in the field. The expenditure on development work in West Germany is of the order of $2 to $3 million per year.

The Japanese Effort. A very extensive effort directed toward open-cycle MHD [13–15] power generation with experiments on all phases of MHD central power plants is being conducted in Japan. The generator channels tested have been largely the segmented Faraday design with some work performed on the Hall generator configuration as well. A number of preheater designs have been run with special attention paid to the seed buildup that occurs under some working-gas conditions in these devices. Methods of improving channel duration and preheater operation are being investigated presently. The approach in Japan to the preheater problem differs from that in the Soviet Union in that tubular preheaters are being investigated, rather than the regenerator type. Some progress has been made in all of these areas. Fig. 7 shows the estimated power-demand curve for Japan as given in "The Present Status of MHD Power Generation in Japan" by the MHD Power Generation Study Team and T. Sekiguchi at the University of Tokyo. This shows a relatively modest power requirement by the year 2000, approximately equal to that expected by the U. S. by the year 1980. It is very plain that the Japanese expect to get uranium from the U. S., as does much of the western world. Agreement to furnish the western world with uranium for their reactors is contained in the June 4 message to Congress by President Nixon when he said "Plant expansions are required so that we can meet the growing demands for nuclear fuel in the late 1970's—both in the United States and in other nations for which this country is now the principal supplier."

The president is speaking here of the uranium-enrichment plants; however, we must also supply the uranium to be enriched. The Japanese currently view MHD as chiefly a peak-load technology. This stems from the Japanese economy in which the main source of fossil fuel is expensive oil from Indonesia. Thus, as in many countries other than the U. S., the burning of uranium rather than fossil fuel presents an economic advantage. In the U. S., the reverse is true.

Other Countries. Numerous other open-cycle MHD

Fig. 6 Exit view of the West German Garching MHD generator.



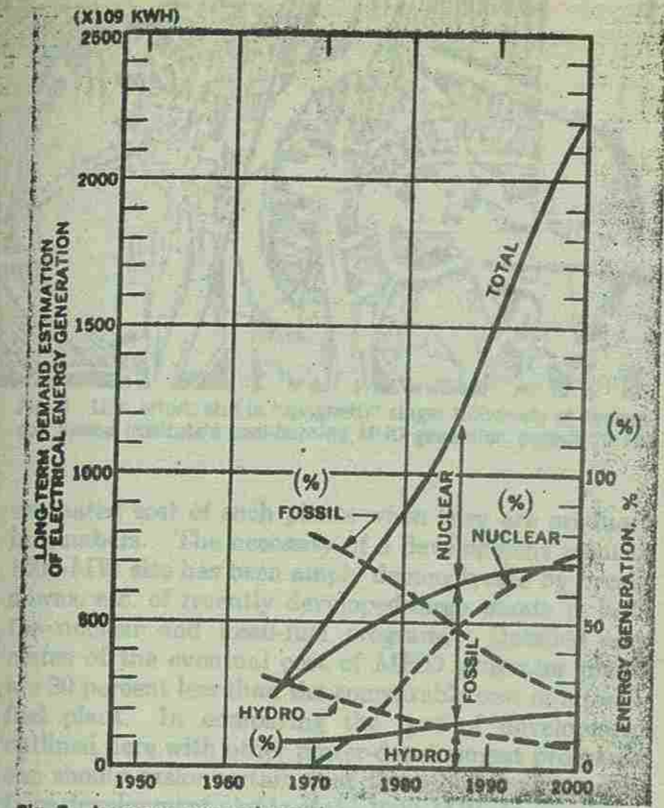


Fig. 7 Japanese power demand.

efforts exist in other countries, such as the large one in Poland and the beginning of a significant national program in Canada. In the British Isles and in France the MHD effort has been reduced partially because of the economy and partially because there fossil-fuel power, in general, does not have the advantage of very low fuel costs that it does in the U.S.

MHD Status in U. S. Within recent years in the U. S. there has been literally no central-power MHD program other than the small efforts that could be maintained in industries and the universities using their own funds to work on central power on the side. The vast majority of the work has been in basic research on basic phenomena and development work for the Defense Department. During 1971, funds have become available to start a minimal amount of central-power MHD work. This is largely being funded by the Office of Coal Research in cooperation with power companies. The largest such effort is under a contract let to Avco and a group of utility companies to work on clean-fuel peaking plants with a small amount of coal-burning included. This contract is of the order of magnitude of $2.6 million to be spent over three years. Additional amounts would come from Avco and the associated utilities. The next largest contract is with the University of Tennessee Space Institute, with $324,000 to be spent over one year on power generation with coal and char fuels. This work includes a small investigation of chemical regeneration. Of the total funds, $261,000 is being furnished by the Office of Coal Research, $50,000 by the Tennessee Valley Authority, and $30,000 by the university. It is expected that a contract for approximately $100,000 per year will be let to M.I.T. to perform some basic research studies and to advise the Office of Coal Research. In addition to this, STD Corp. of Los Angeles may receive approximately $90,000 to direct and operate a master computer program designed for MHD power-system analysis. At Stanford University there will be a research program funded by the Electric Research Council and the Bureau of Mines.

Avco, Stanford, and the University of Tennessee Space Institute all have a long history of continuous research and development on open-cycle MHD power generation and have additional MHD open-cycle work funded from other sources. The total central-power program in the U. S. is inadequate to make appreciable progress in this area, but there is the anticipation that additional money will be available in the fiscal 1972 appropriation by Congress and from the Electric Research Council to expand this program. As a matter of fact, all of the efforts enumerated here are preliminary to a national program to be agreed upon by the Office of Coal Research and the Electric Research Council. The participants in the initial program have plans for such expansion when the resources are made available.

It is very unlikely that a decision to develop power generation at a minimum cost will ever come about in the U. S. It is thus impossible for us to follow the bread-board plan of experimentation that is being pursued at the High Temperature Institute in Moscow. In general, programs in the U. S., which do not have heavy support within the government, have to start with low-level funding on relatively inefficient feasibility demonstrations. As the need for the end product of development nears and becomes more evident, the pace is stepped up and extra money must be appropriated to make up for lost time. A better development plan is shown in Table 2 where feasibility of components is demonstrated at the more realistic 20-MW size for MHD power. In the next stage, overlapping somewhat, is a pilot plant to be designed to obtain efficiency data that can be extrapolated to full-size construction. Finally, a 1000-MW plant is included at twice the

TABLE 2 MHD Development Cost Plan

Fiscal year	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982
R&D	0.6	4.0	4.0	5.0	6.0	6.0	6.0	6.0	6.0	7.0	7.0	7.0
20-MW plant			4.1	11.9	10.0	2.0	1.0	1.0				
100-MW plant					3.4	11.4	28.8	25.0	4.0	3.1		
1000-MW plant							2.0	26.2	60.3	101	72.0	2.9
Yearly total	0.6	4.0	8.1	16.9	19.4	19.4	37.8	58.2	70.3	111	79.0	9.9
Gross cost of program												434.7
Less sale of power												20.2
Less residual worth of plant at one-half of construction cost												132.0

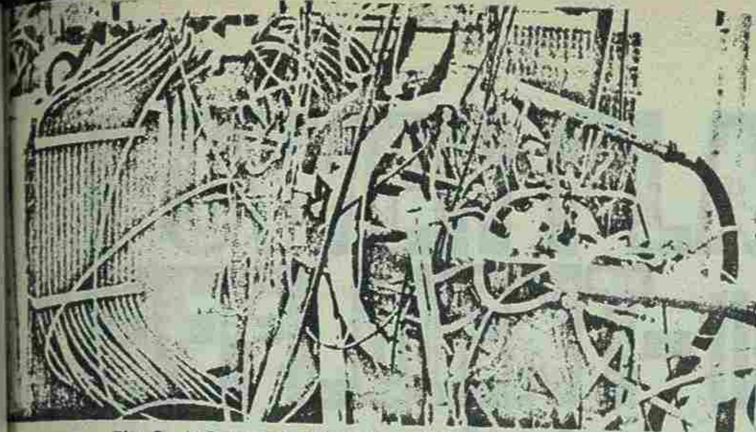


Fig. 8 U.S. effort, still in "spaghetti" stage: University of Tennessee Space Institute's coal-burning MHD generator, output 70 kw.

estimated cost of such plants when they are produced in numbers. The necessity of a development plant of 1000-MW size has been amply demonstrated by breakdowns, etc. of recently developed large plants in both the nuclear and fossil-fuel programs. Detailed estimates of the eventual cost of MHD generator plants are 30 percent less than the comparable cost of a fossil-fuel plant. In comparing the cost of development outlined here with other power-development programs, one should make certain that the other program contains development plants of the 1000-MW size.

If instead of a program such as the one advocated here, the country embarks on several years of basic work performed with apparatus of very small size, some of the important cost savings from MHD development outlined in Table 2 and the accompanying text will be lost because of the resulting delay.

As of February, 1972, the line item in the administration's budget for MHD development on central power for fiscal 1973 is \$2.6 million for work outside of the government and \$400,000 for work in the Bureau of Mines. There is, therefore, some chance that a government appropriation of \$2.6 million will be available in fiscal 1973 to match with money obtained from the utilities.

Important for the future of energy development in the U. S. is the energy study being conducted by the Senate Committee on Interior and Insular Affairs. There have been many energy studies instituted during the past year, but none has been satisfactorily constituted, authoritative, definitive, and suitable from the standpoint of providing an information basis suitable for new legislation. An increasing indication that the development being presently [illegible] is unbalanced is evident from the fact that tremendous amounts of development are going on in the nuclear field and almost none in the fossil-fuel field. A department of national resources covering all forms of energy would be the best solution to the balancing problem, but many difficulties now lie between the conception of such a department and its realization. The increased interest in energy on the part of Congress is a bright spot for the future, and we expect that the central-power situation, including MHD, may be profoundly affected by recent legislation, now in committee, introduced by Senator Metcalf in the Senate and various members of the House of Representatives which is aimed at acquiring a national central-power distribution system.

The future of central power is cloudy, with the uranium supply and price difficult to forecast, the breeder reactor uncertain in its development time and acceptance by the public, the conventional fossil-fuel plant now asymptotically approaching its highest efficiency, and the cost of power-plant construction steeply rising along with the price of fossil fuel. All of these conditions make the future of central power in the U. S. uncertain, and predictions exceedingly difficult. It does seem clear, however, that MHD fossil-fuel power generation, if acquired, would do several important things. It would provide economic competition for the nuclear system, give a possible alternative for relatively pollution-free power production if the breeder reactor fails to gain public acceptance, and extend the lifetime of our coal reserves.

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POWER PLANT EFFLUENT—thermal pollution or energy at a bargain price?

Approximately two-thirds of the fuel energy, chemical or atomic, used to make electric power is waste heat. To avoid "thermal pollution" we can use cooling towers. But there may be a better plan: "new-town" applications with 100 percent temperature control of all living space and office working space.

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In early 1970, the Svenska Teknologföreningen (Swedish Association of Engineers and Architects) and other Swedish groups sponsored a worldwide idea contest: "Engeri till Reapris" or "Energy at Bargain Price." It sought out proper uses in the manufacture of electric power for the enormous quantity of residual energy now rejected as heat and largely returned to the water course selected as a source of cooling water. The concepts outlined below were honored by the technical jury.

"New-Town" Applications

The ideal use or uses for the enormous quantity of residual energy from steam electric power plants require large demand, 24 hr per day, 365 days per year. Most of the obvious applications use too little energy.

Also, many uses of energy are available in the winter, but not in summer. Thus, finding large-scale valuable uses of thermal energy in summer without insult to the environment must be a key to developing beneficial uses.

To get the necessary large scale with sound economics, we have been led right back to the source of the demand for electric power—the city and its people. We propose "new-town" applications with 100 percent heating of all living space and office working space. By new town, we mean any area where we do not have the problem to modify existing buildings, their equipment, and utilities. We include the free-standing new town, the new-town-in-town, and satellite towns adjacent to existing large cities.

The total energy used in the U. S. for air conditioning is roughly equivalent to the total energy used for residential and office space heating. Although the low-grade energy typically dumped from electric power generation is not readily usable for air conditioning, it is possible to stop the expansion of steam at a temperature slightly in excess of 94 C and use the residual energy to drive an absorption refrigeration system, such as a lithium bromide–water system.

The criterion of minimum heat rate for electric power generation should be abandoned in favor of a systems approach to the use of fuel energy in an energy center in a new town in which the overall system for production of electric power *and* residential and office space heating and cooling is optimized. The economic results appear promising. Further elaboration will show additional benefits as we look at diversified applications of residual thermal energy, particularly spring and fall uses.

Optimization of an Energy Center

Central plants providing heat to many residences are certainly not new. An excellent example is the use of the geothermal hot water in Iceland for the past 45 years for home heating now serving 81,000 people in the vicinity of Reykjavik, described by Bodvardsson [1].[3] The costs compared to other sources of energy for heating are quite favorable. Bodvardsson's data show an average cost of 60 percent compared to the cost of similar heating with fuel oil. There are also some 50 district heating utilities operating in the U. S.

For summer cooling, a heat-driven refrigeration system is needed to provide chilled water into the homes and office space. A lithium bromide–water absorption system looks like a good candidate. It requires hot fluid input at about 94 C. This would require energy from the energy center at a higher temperature than 94 C to provide for transmission losses. A turbine extraction temperature of about 100 C with good thermal design of the transmission lines should provide for transmission losses for a large-size city. The 15.3-km line connecting the thermal area at Reykir to the city of Reykjavik in Iceland has an average temperature drop of only about 3 C.

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Based on a paper contributed by the ASME Energetics Division.

[3] Numbers in brackets designate References at end of article.

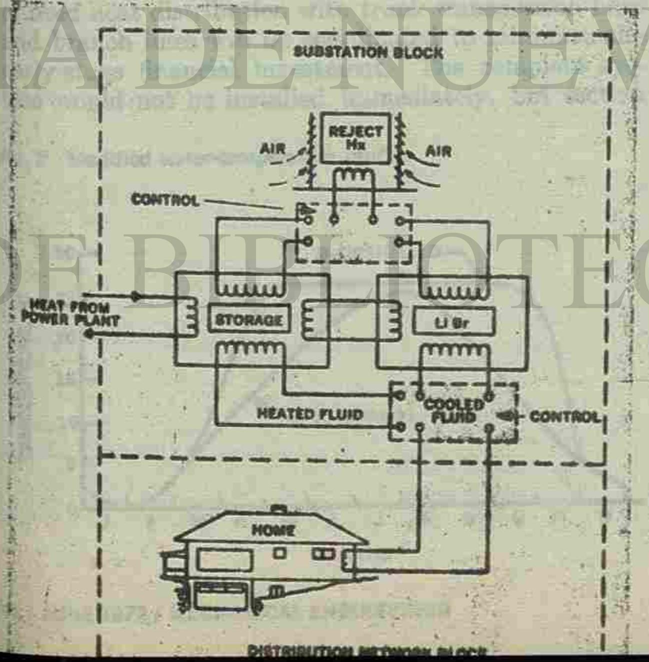
An excellent match exists between the peak power demand for home heating in winter and for home cooling in summer. A three-bedroom home in New York City or St. Louis might require a peak of 50,000 Btu/hr for heating and 24,000 Btu/hr extraction for cooling. Since the coefficient of performance (COP) of a good lithium bromide-water refrigeration system is about 0.5, the summer driving power peak would also be about 50,000 Btu/hr.

The compatibility of this approach with the patterns emerging in new-town planning should be investigated. The typical present approach to planning new towns includes the concept of building up the complete town starting with many small groupings of perhaps 500 people in 150 residential units free of through automobile traffic, and is known as a cluster. The town plan is built up by analyzing what it is that various-sized groups of people need and want in a town, including communication, transportation of people and goods, waste management services, social facilities, education, etc. Perhaps four clusters are grouped together to form a neighborhood of 2000 people. Perhaps six neighborhoods form a village of 12,000 people. Perhaps six villages make up a town of 72,000. Perhaps six towns make up a city of 400,000 plus. There might be one major cultural center for the entire city, one high school for each town, a major shopping center for each village, etc.

We envision one energy center producing electric power for the entire city or town and providing excess electric power for export. Underground transmission of energy flows as hot fluid to a substation in each cluster of 150 residential units. Each substation processes the energy and distributes hot fluid in winter and chilled fluid in summer to each residence, Fig. 1.

The daily load profile for each substation will show typically a peak heating demand in the early morning with a dip in the afternoon, or an air conditioning peak in the afternoon with a dip in the early morning hours. These peaks should be accommodated by providing an energy-storage insulated water tank at each substation to "flywheel" the demand.

Fig. 1 Schematic of apparatus for year-round home conditioning via substations.



Preliminary estimates show favorable costs compared to our present conventional practice for the services provided by the substations. The substation system must be charged with the value of the electric power not generated because of the early extraction of steam, as well as the costs of transmitting the hot fluid, processing it, and distributing it to the residences. The power not generated because of complete steam extraction at 100 C would amount to about 15 percent of the maximum nominal station rating for a fossil-fuel plant or about 26 percent for a typical nuclear power plant. Some saving is available from flattening of peak demand by grouping requirements for 150 residences into one substation and from flywheeling. This should be conservatively 15 percent. A credit might be taken for the dry cooling tower which is eliminated. Each substation acts as a small dry cooling tower with a heat exchanger discharging unused heat to the air. The system of substations is superior to a central dry cooling tower since it distributes the heat dissipation over the entire city area.

Costs chargeable to heating and cooling will be dependent upon site and upon plant design, and will be quite variable. Preliminary cost studies indicate hot-fluid generation costs typically 10 to 18 cents/10^6 Btu. Transmission costs vary between 5 and 30 cents/10^6 Btu. Processing and distribution costs might range from 15 to 60 cents/10^6 Btu. Miller et al. [2] have made extensive studies of the cost of fluid heat transmission and distribution based on steam heating practice for the federal Department of Housing and Urban Development.

We have projected cost estimates for an example substation of the energy center for a new town as follows:

- Town of 138,000 people, 275 clusters, over 25 sq mi
- Combination-cycle fossil-fuel gas turbine-steam turbine 250-MWe energy center
- 150 residential units in cluster, each with 50,000 Btu/hr
- Peak total demand at substation of 6.4×10^6 Btu/hr or 1.9 MW
- 3½-mi transmission line consisting of 3 mi of 10-station trunk and ½ mi of single-substation line
- 40-acre cluster site
- Average distribution distance within cluster, 350 ft.

Major cost items for one substation are estimated at:

- Transmission-line cost, $24,000
- Substation cost, $40,000
- Distribution lines, $133,000.

Costs are based on excavation and installation of piping prior to street paving. The transmission line includes thermal insulation.

The distribution piping system is earth-insulated and of low pressure rating to carry water heated below 90 C from the substation to the homes. This piping assumption greatly reduces cost of the distribution piping system. Further economy of piping is achieved by alternating the heating and cooling functions on a single piping system. This seasonal shift in late spring from heating to cooling and in early fall from cooling

TABLE 1 Estimated Costs for Example Energy-Center Substation for Heating and Cooling

Annualized Costs		
Electric power loss	$ 6.0	K/yr
Transmission	$ 3.4	K/yr
Substation	$ 5.6	K/yr
Distribution	$ 19.2	K/yr
Operation and maintenance	$ 0.7	K/yr
Net total	$ 34.9	K/yr
Cost per residence	$233	/yr
Allowing credit for cooling tower	$ 18	/yr
Cost per residence	$215	/yr

to heating involves transient heat losses that, averaged over the year with the steady-state losses of mid-winter and mid-summer, are comparable to those of conventional insulated steam heating systems.

A dry cooling tower for the combined-cycle 250-MW energy center with 50 percent steam turbine at $40/kw would be $5,000,000.

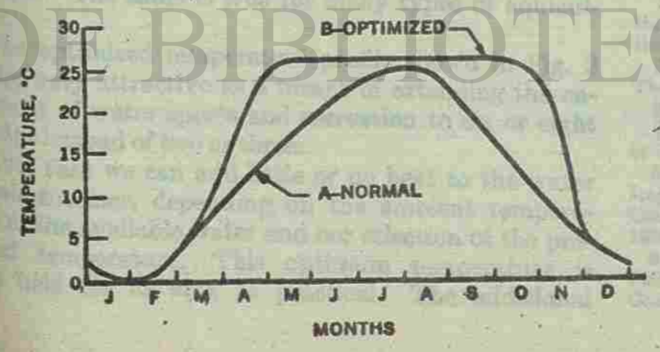
Table 1 shows estimated annualized costs per substation and per residence.

For comparison, the same residential units equipped with individual standard heating and air conditioning units exclusive of distribution within the home would represent an initial cost to each homeowner of approximately $1400 at retail and an annualized cost including fuel of about $520. If this were restated in basic costs for a volume representative of an entire city, the cost would be at least $260 per residence. Thus, the estimated costs permit a satisfactory selling price which is still quite a bargain to the buyer. For high-rise residential or other high-density use, the costs are still more favorable.

For lower density and greater transmission distances, the costs are less favorable, but still promising.

A characteristic of the well-planned new town is design to minimize cost of infrastructure and lead time of costs. It may be assumed that in a well-planned new town there will be an optimized staging plan for year-by-year town development and that the system of fluid heat distribution with trunk transmission lines and branch lines will be coordinated to minimize the early-stage financial investment. The complete system would not be installed immediately, but section by section as needed. In the initial stages before the energy center has been completed, the first few clusters might be served by temporary boilers.

Fig. 2 Modified water-temperature profile.



Other Uses

If we go no further than to provide energy centers in our new towns which optimize electric power production and living-space temperature control for reduced total cost and less harsh impact on the physical environment, we have made good progress. There are, however, additional benefits available.

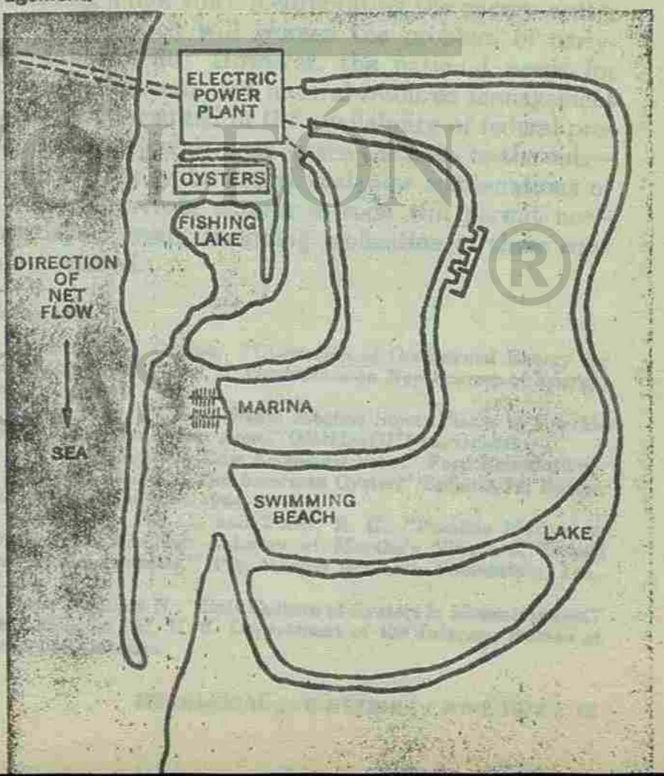
As Harrison [3] points out, diversity in our systems increases stability. He also urges movement toward recycling and closed systems. We should introduce additional uses of residual thermal energy for stability and balance, as well as for their direct benefits.

In a general sense, given the availability of large quantities of water in a new town, there is much that can be done to improve the quality of living. Many of the most charming cities of the world owe much of their charm to the presence of extensive open water. Low-cost, modern earth-moving techniques make creation and exploitation of lakes, lagoons, and canals practical in a new town. We can add aesthetic appeal, multiply waterfront footage for residential property, provide fishing, provide water sports and recreation, provide an extensive heat-sink system, and provide bodies of water for commercial use.

Several electric utilities have made a start in this direction by creating artificial ponds for cooling of new power-generating facilities, and providing fishing and recreational use of ponds as a bonus.

Heating and cooling give us a good balance between mid-summer and mid-winter load peaks and leave available large quantities of heat in spring and fall. The heat energy from conventional heat exchangers after full steam expansion can be used to bring a large body of water to optimum temperature for aquiculture and hold it there for six to eight months, Fig. 2.

Fig. 3 Example of site sculpturing for water and energy management.



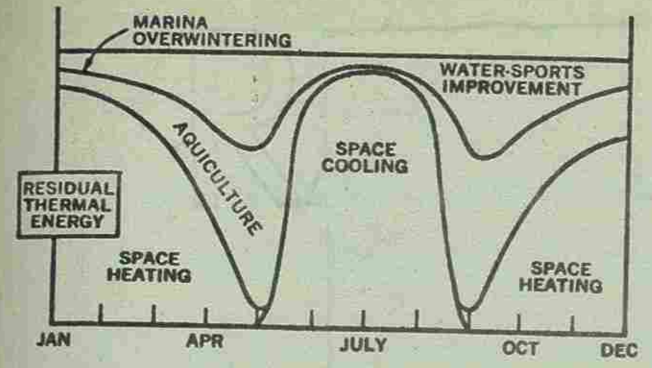


Fig. 4 Concept of using thermal energy throughout the year.

Most fin fish and shell fish under natural conditions live in water which is, for most of the year, substantially too cold for optimum growth rate. The optimized temperature profile shown in Fig. 2, if applied for example to Chesapeake Bay water, could result in raising oysters to marketable size in one season instead of three or four seasons.

There is a large and growing body of knowledge in marine and fresh-water bionomics pertinent to aquiculture which has been largely unexploited to date. There are many promising application opportunities for shell fish and fin fish aquiculture in marine and fresh water. These opportunities include use of selective breeding to optimize ease of culture and marketability of the product. They include selection of uncommon species, perhaps from other parts of the world, which have particularly attractive market features.

Oyster farming in Japan and Australia is now large scale, but primitive in technique and very labor-intensive. Considerable knowledge of and experimental techniques for oyster culture have been developed in this country [4–6], but they have yet to be utilized on a large scale.

The early small-scale experiments in this country are characterized by improvisation. Oysters have been grown on "strings" of oyster shells on wires suspended from a spar. Trays are also frequently used. Extrapolating densities and yields achieved indicates that an oyster farm should yield an annual crop worth $40,000 per acre per year with application of energy-center heat. The knowledge available needs to be put to use with appropriate engineering skill and cost management.

Although many questions concerning optimization of techniques remain unanswered, the substantial body of knowledge and experience in hand should support a well-managed oyster-farming project relying on residual thermal energy from an energy center for optimizing various steps of oyster culture and oyster food culture. The same is true for many types of aquiculture.

The optimized temperature profile shown in Fig. 2 is also very attractive as a means of extending the enjoyment of water sports and recreation to six or eight months instead of two or three.

Note that we can add little or no heat to the water in mid-summer, depending on the ambient temperature of the available water and our selection of the preferred temperature. This optimum temperature is then held for as long as practical. The additional heat is discharged to the air as shown in Fig. 1.

Fig. 3 shows a schematic illustration of water exploitation in a new town. Fig. 4 illustrates the concept of a uniform load of thermal energy use throughout the year.

An inventory of beneficial uses should be developed with assurances that new-town planners have access to this store. Some otherwise insufficient uses become important bonuses to provide off-peak thermal load. Melting snow from streets and sidewalks, for example, cannot stand alone, but may contribute a bonus in the well-planned and optimized new town.

Some of the other potential uses require steam, some require hot fluid at somewhat enhanced temperature, and some use low-grade thermal energy as normally discharged from a steam electric power plant.

Uses of steam for industrial processing combined with power generation have been demonstrated to be advantageous. Sewage distillation with steam from the energy center may be made advantageous with proper planning.

If greenhouses and/or phytotrons can be justified in the new town, a small economic bonus can be obtained by heating with low-grade thermal energy from the energy center. Preliminary studies show that biological processing of sewage can be accelerated by raising the temperature using low-grade heat. Gains of a factor of 10 appear reasonable. This means that for a given plant size, the throughput might be increased by a factor of 10.

Future Prospects

Entrepreneurs who undertake to build new towns for financial gain are more often disappointed than successful. To quote Mr. Joseph Taravella, president of the successful Coral Ridge Properties, "New town building should be approached with humility." The key problems are an underestimate of the early-stage financial investment, or an overestimate of the pace of growth and hence profit potential, or more typically both.

Building a new town incorporating the energy-center concept discussed will worsen the problem of early-stage investment. However, the national needs for urban development and natural-resource management have already resulted in the availability of federal program assistance which can lessen the risks to the entrepreneur. It may be hoped that new combinations of federal and private enterprise soon will permit new-town development, including realization of these concepts discussed.

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R ATION

Part 1—Recent Advances and Trends

Here's a survey of changes in the field of radiation thermometry over the past decade. Considerable advantage has been derived from operating modern photodetectors in selected spectral regions, and extension of the low-temperature limit by use of infrared radiation. Highly accurate automatic versions of disappearing-filament optical pyrometers have been developed for high-temperature applications. Criteria for selecting wavelength and spectral bandwidth appropriate under various circumstances are given with special emphasis on effects of atmospheric spectral absorption and spectral emissivity.

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Radiation thermometry has long played a vital role in industrial and laboratory measurement of temperatures. It is unique among temperature-measurement methods in that direct physical contact with the object whose temperature is being measured is not required. At very high temperatures there is no alternative method, since contact thermometers degrade too rapidly to be useful, or they simply melt or vaporize. This noncontact characteristic is, however, a mixed blessing. The physical laws that govern the behavior of thermally emitted radiation are not always in concert with the desires of those who must use thermal radiation as a means of measuring temperature, and in general such methods require more knowledge on the part of the user than do the methods of contact thermometry.

Radiation Temperature Scale

Radiation thermometry is based on the concept of blackbody radiation, illustrated in Fig. 1, for which spectral radiance is an exactly known function of the absolute temperature of the blackbody as given by the Planck radiation function.

$$N_{b\lambda} = C_1\pi^{-1}\lambda^{-5}(e^{C_2/\lambda T} - 1)^{-1} \qquad (1)$$

where

N_λ = spectral radiance (radiant power per unit projected target area per unit solid angle per unit wavelength interval)
$N_{b\lambda}$ = spectral radiance of a blackbody
C_1 = the first radiation constant
C_2 = 0.01438 m·K, the second radiation constant
λ = wavelength of electromagnetic radiation
T = absolute temperature of the blackbody.

Equation (1) is used to define the International Practical Temperature Scale (IPTS) at temperatures above the freezing temperature of gold. Late in 1968, the IPTS was again updated [1][2] and is now designated IPTS-68. A significant change in terms of radiation thermometry was the new value assigned to the freezing temperature of gold (1064.43 C ± 0.2 C), about 1.4 C higher than the previous value. The value assigned to C_2 was changed from 0.01438 to 0.014388 m·K. If $C_2/\lambda T \gg 1$, Planck's radiation law may be replaced by the mathematically simpler approximate form known as Wien's law:

$$N_{b\lambda} = C_1\pi^{-1}\lambda^{-5}\, e^{-C_2/\lambda T} \qquad (2)$$

Although equation (1) is used to define the IPTS, the accuracy of equation (2) is adequate for most calculations in the analysis of radiation thermometry.

Since about the turn of the century, radiometry has been employed as a means of temperature measurement, and until the development and widespread application of modern photodetectors only two general classes of radiation thermometers have been available. These have been the "disappearing-filament optical pyrometer," or minor variations thereof, and the so-called "total-radiation pyrometer."

Disappearing-Filament Optical Pyrometer

The disappearing-filament optical pyrometer had reached a state of essentially complete development by about 1920 [2], with practically no significant change since then. It measures the nearly monochromatic radiance of a high-temperature source and indicates the temperature of a blackbody radiator having the same spectral radiance.

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[1] Assistant Director, Instrumentation Systems Center.
Based on a paper contributed by the ASME Research Committee on Temperature Measurement. This survey was based on work supported by the Pyrometer Instrument Co., Inc., Northvale, N. J.

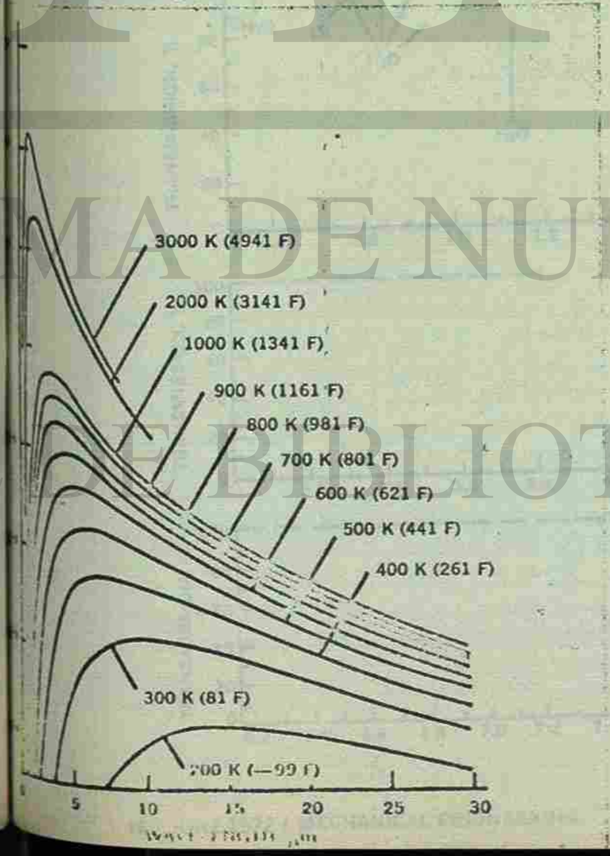
[2] Numbers in brackets designate References at end of article.

ERMOMETRY

Because it has been, until recently, the most accurate strument with which to measure high temperatures, has been fully developed and exhaustively studied. has been used to realize the International Practical mperature Scale at temperatures above the freezing mperature of gold, and its properties are extensively ported in the literature [3, 4]. Unfortunately the rature has been too little read by the users. Al- ough the instrument will not be elaborated upon re, a brief description will be helpful to those not miliar with its construction and mode of operation, well as helpful in providing a background for what follow.

The disappearing-filament optical pyrometer is es- ntially a low-power terrestrial telescope in which a ngsten-filament vacuum lamp has been placed in e focal plane of the objective lens. A red glass ter is located between the lamp and the eyepiece. hen the telescope is sighted on an object or "target" whose temperature is sufficiently high that it glows visibly—the low-temperature limit on this type of pyrometer is 700 to 800 C, depending on several factors—the image of the target is formed in the same plane as the lamp filament. To the observer, viewing through the eyepiece and red filter, the magnified image of the lamp filament is seen superimposed on the image of the target. By adjusting the current through the lamp filament, the luminance, or brightness, of the lamp filament may be adjusted to match that of the target. Because the image is nearly monochromatic red (nominally 0.65 μm), no color difference is seen between the lamp filament and the target, and the filament seems to "disappear" against the background of the target. Under these conditions, the pyrometer is said to be photometrically "matched." By viewing a blackbody at various known temperatures [3] the pyrometer lamp current can be calibrated as a function of blackbody temperature. For target temperatures above 1300 or 1400 C a neutral "gray" absorbing glass filter is placed between the pyrometer lamp and the objective lens. This has the effect of providing a higher range for the pyrometer. Most such pyrometers are equipped with two or more such filters to extend their range to any desired upper limit.

Fig. 1 Spectral radiance of a blackbody as a function of wave- gth and temperature.



Total-Radiation Pyrometer

The "ideal" total-radiation pyrometer would measure the radiance of a target, i.e.,

$$N = \int_0^\infty \epsilon(\lambda)N_b(\lambda, T)d\lambda \qquad (3)$$

where $\epsilon(\lambda)$ is the spectral emissivity of the heated surface, and will be discussed in more detail in a later section. For a blackbody, where $\epsilon = 1$,

$$N_b = \int_0^\infty N_b(\lambda, T)d\lambda = \frac{\sigma}{\pi}T^4 \qquad (4)$$

The signal S from a total-radiation pyrometer is dependent upon the difference between approximately the fourth power of the absolute temperature of the target and approximately the fourth power of the absolute temperature of the detector. Thus the typical lower useful limit for total-radiation pyrometers is approximately 100 C, although some are used below that temperature. Such instruments have been studied in great detail and are well described in the literature [5, 6]. For purposes of the present discussion, it is sufficient to note that the signal depends upon the radiance of the target after it has been attenuated by atmospheric transmittance, $\mathfrak{J}_a(\lambda)$, Fig. 2,[3] and the transmittance of the optical system, $\mathfrak{J}_o(\lambda)$, as well as modified by the responsivity of the thermal detector, $R(\lambda)$.

In virtually all cases the term total-radiation pyrometer is to a considerable extent a misnomer. Energy absorbed by the detector is converted to heat, causing the absorber temperature to rise above that of its surroundings until the rate of radiant heat input to the detector is equal to the rate of heat loss from the detector by means of conduction, convection, and radiation. The signal ultimately depends upon the temperature of the detector, which is therefore classified as a "thermal detector." The signal (after correction for the effect of ambient temperature) will be proportional to the integral of the product of a number of terms that are functions of wavelength, i.e.,

$$S(T) \sim \int_0^\infty \epsilon(\lambda) N_b(\lambda, T) \mathfrak{J}_a(\lambda) \mathfrak{J}_0(\lambda) R(\lambda) d\lambda \qquad (5)$$

$$S(T) = \epsilon_T T^n \qquad (6)$$

The primary application for such pyrometers has been at temperatures below that to which the disappearing-filament optical pyrometer was applicable, or where automatic recording or controlling of temperature was essential. In common practice [7, 8] the value of ϵ_T and the value of n are determined for each instrument and each application in a restricted temperature range. Because of its very broad spectral bandpass, such an instrument cannot be expected to exhibit a high degree of reproducibility if either $\epsilon(\lambda)$ or $\mathfrak{J}_a(\lambda)$ is variable in some portions of the spectrum. Variations in $\mathfrak{J}_a(\lambda)$ are ordinarily minimized by reducing the target distance as much as possible.

New Class of Radiation Thermometers

It should be clear that within the two classes of instruments described, industrial and laboratory applications have not had access to radiation thermometers that can measure temperature with reasonably high accuracy and that are also capable of both measuring and recording over most of the temperature range important in industry. Since the advent of modern photodetectors, that picture has begun to change, with rapid progress having been made in the past 15 years.

The initial change came primarily with the application of photomultipliers in place of the eye [9–11], and in automating [12, 13] the disappearing-filament optical pyrometer. One such instrument developed by the author [14] is described in a previous publication. High resolution is attained with this instrument and an indication of its accuracy [15], together with the accuracy of realization of the IPTS [16], is shown in Table 1.[4]

About half of the uncertainty of the automatic optical pyrometer as indicated in Table 1 is due to instability in the pyrometer lamp [17, 18], and most of the remain-

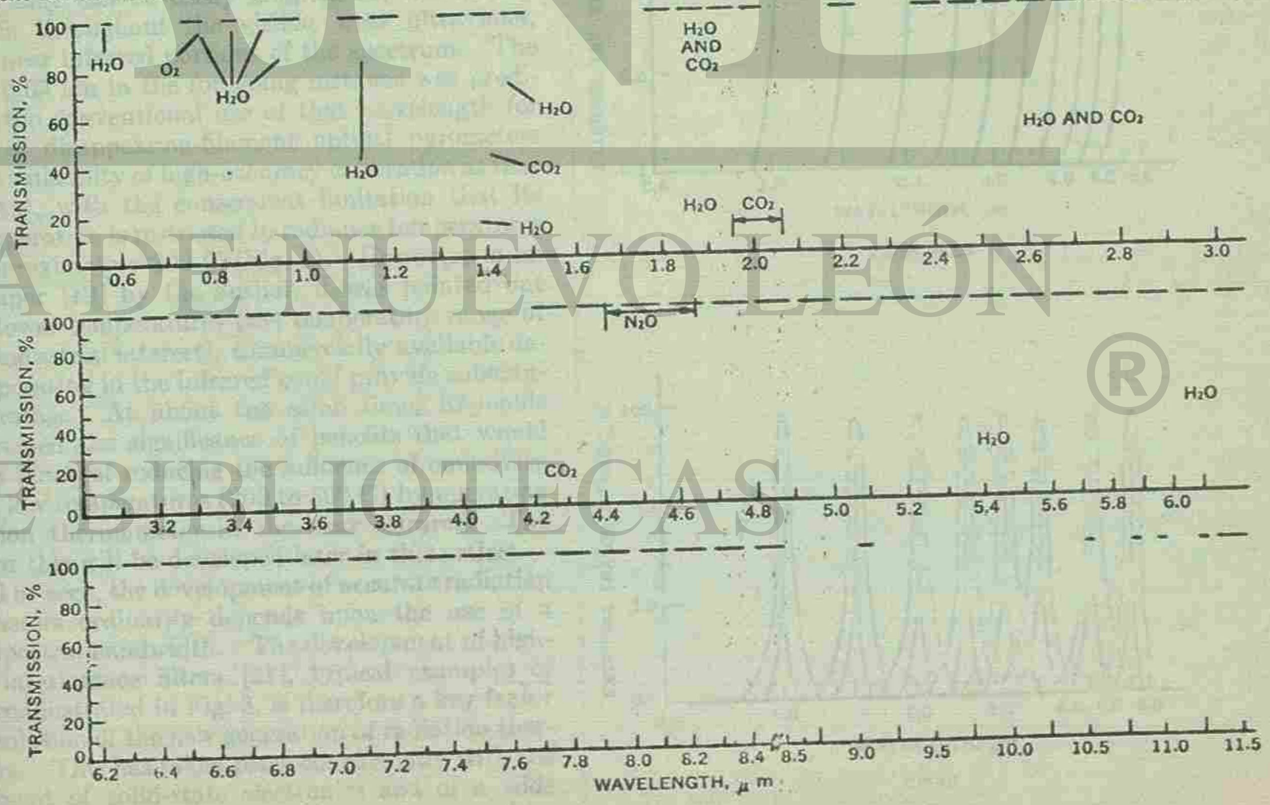


Fig. 2 Atmospheric spectral transmittance at sea level over a 0.3-km path containing 5.7 mm precipitable water at 79 F and 22.5 percent relative humidity. Adapted from Wolfe [22, pp. 252-254].

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[3] Transmittance varies approximately as an exponential function of path length and humidity, and is substantially greater at shorter distances. Nevertheless, the dominant absorption bands are very much apparent even at a distance of 1 m.

[4] Based on a preliminary analysis by Lewis and Kostkowski [15]. Effective wavelength is determined with an uncertainty of 0.2 nm. Calibration drift rate for a typical pyrometer lamp is about 0.01 C/hr, but may vary substantially from one lamp to another. The upper part of the table shows the results of a recent intercomparison of strip-lamp calibrations among four national laboratories, as presented by Lee et al. [16]. Maximum estimated uncertainties at the temperatures tabulated varied among the participating laboratories. The range of the estimated values is given in the table.

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TABLE 1a International Comparison of Strip-Lamp Calibrations on IPTS-68

Temperature	(°C)	1064	1100	1200	1300	1400	1500	1600	1700	2200
Estimated Uncertainty	(°C)	.09-.12	.11-.15	.12-.17	.16-.20	.19-.22	.22-.25	.25-.29	.29-.43	.54-1.8

TABLE 1b Typical Uncertainty of Initial Calibration of Automatic Optical Pyrometers on IPTS-68 at the 95 Percent Confidence Level

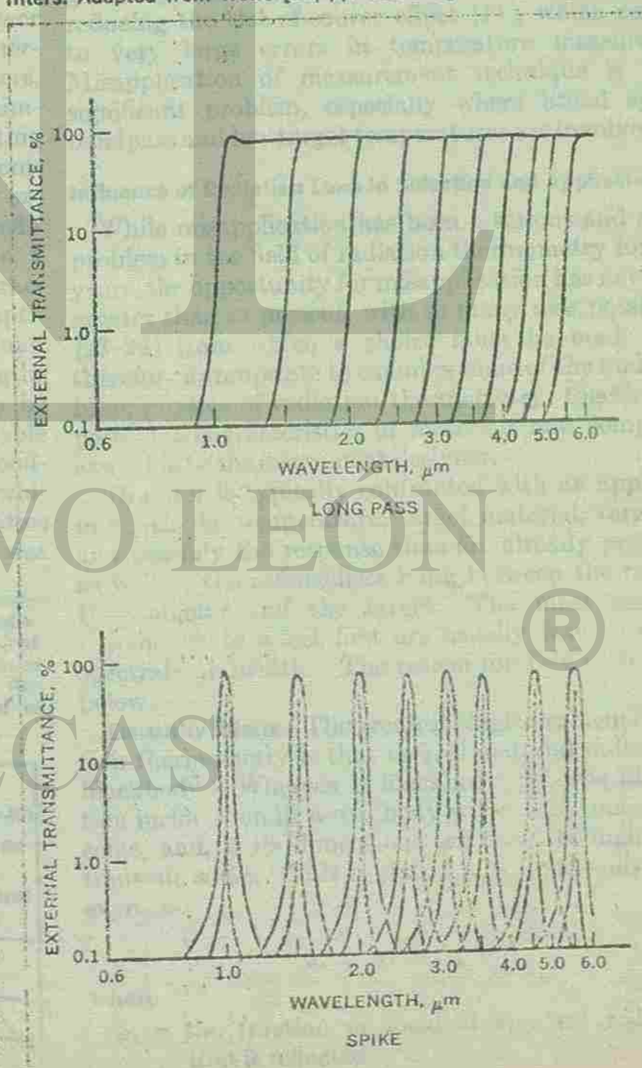
Range		Range 1			Range 2			Range 3			Range 4		
Temperature	(°C)	800	1064	1235	1100	1400	1750	1500	2300	2725	2500	2725	3524
IPTS uncertainty (NBS)	(°C)	.5	.12	.15				.32	1.5	2.4			
Pyrometer instability	(°C)	.5	.4	.4				1.3	1.4	1.6			
Transfer error	(°C)	.2	.2	.21				.4	.5	.5			
Maximum error	(°C)	1.2	.7	.8	1.2	1.2	1.6	2.0	3.4	4.5	5.8	5.7	8.7

ing uncertainty is associated with the IPTS. Quinn and Lee [19] have recently developed vacuum tungsten-strip lamps having long-term calibration instability not greater than 0.1 C/1000 hr, about a factor of a hundred improvement over presently used pyrometer lamps. The extent to which this improvement can be incorporated into pyrometer lamps is yet to be determined.

Automatic optical pyrometers of the type described operate at the conventional wavelength of 0.65 μm. However, they can be easily adapted for use at any wavelength throughout the visible, near ultraviolet, and very near infrared portions of the spectrum. The choice of 0.65 μm in the foregoing instance was predicated on the conventional use of that wavelength for purposes of disappearing-filament optical pyrometers (and the availability of high-accuracy calibration at that wavelength), with the consequent limitation that its range of operation is restricted to radiance temperatures above approximately 800 C (Fig. 1). However, in an earlier paper [12] by the author, it was pointed out that for lower temperatures (the temperature range of greatest industrial interest), commercially available detectors operating in the infrared could provide substantial advantage. At about the same time, Reynolds [20] discussed the significance of benefits that would accrue in terms of reducing the influence of emissivity errors at low temperatures (200 to 500 C) by operating a radiation thermometer in the near infrared. The reason for this will be developed later in this article.

As will be seen, the development of accurate radiation thermometers ordinarily depends upon the use of a narrow spectral bandwidth. The development of high-quality interference filters [21], typical examples of which are illustrated in Fig. 3, is therefore a key factor in the evolution of the new generation of radiation thermometers. This has taken place concurrently with the development of solid-state electronics and of a wide range of photodetectors [22] suitable for use in various

Fig. 3 Typical examples of commercially available interference filters. Adapted from Wolfe [22, pp. 299-306].



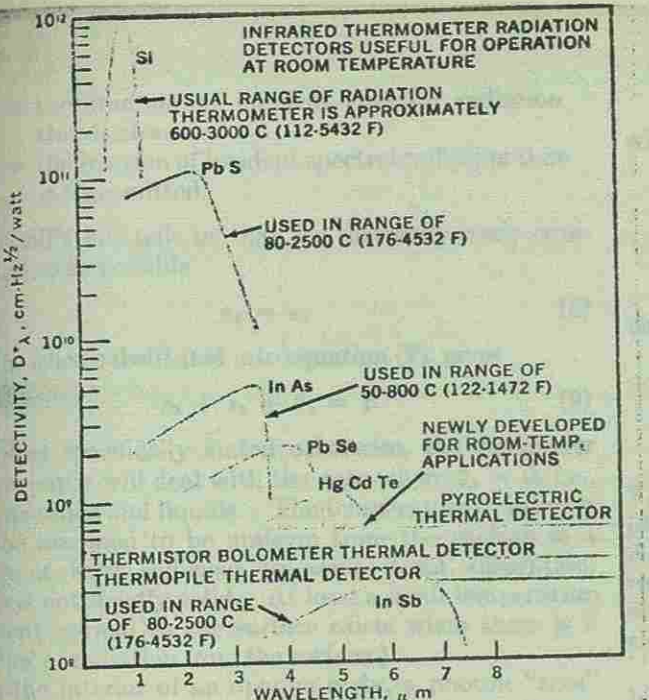
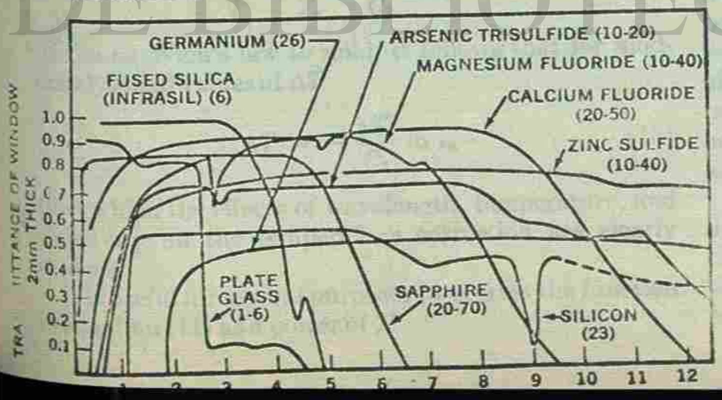


Fig. 4 Infrared detectors of special interest in radiation thermometry. Hg-Cd-Te curve courtesy of Honeywell, Inc. Pyroelectric-detector curve courtesy of Barnes Engineering Co. Other curves adapted from Wolfe [22, pp. 473-499].

portions of the infrared spectrum. Typical examples of photodetectors of interest in infrared-radiation thermometry are shown in Fig. 4.

Infrared-radiation thermometers measuring lower temperatures, but with performance capabilities otherwise similar to those of automatic optical pyrometers, are technologically feasible. However, even the simplest optical components made of infrared-transmitting materials suitable for such use, some of the more common of which are illustrated in Fig. 5, are relatively expensive. Their cost represents a significant impediment to the development of such instruments on a commercially available basis at an economically attractive price. A comparison of the cost of infrared optical systems made of the various available materials and having comparable performance at selected wavelengths is unwieldy, at best. Yet a rough estimate can be made by comparing the cost of commercially available windows—25 mm diameter by 6 mm thick with good-optical-quality surfaces—with the cost of similar windows made of a good-quality optical glass. The ratios appear in parentheses in Fig. 5. (No attempt was made to include a comparison of the cost of a mirror optical system.) This accounts in large measure for the relatively simple optical systems presently employed in most infrared-radiation thermometers, with the corresponding penalty in terms of accuracy, size-of-source effect [14], and long-term repeatability relative to that of automatic optical pyrometers.

Fig. 5 Spectral transmittance of infrared optical materials, nominally 2 mm thick, that are of practical interest to infrared-radiation thermometry. A group of infrared-transmitting glasses (not shown here) has also been developed; their transmission curves typically lie between those of fused silica and sapphire. Approximate cost relative to optical-quality glass is indicated in parenthesies.



It is still not possible to design a general-purpose radiation thermometer that will "solve all of the problems," and there are still problems for which no solution has yet appeared. However, large numbers of previously intractable problems have already yielded, in whole or in large part, to the new designs, and more progress is to be expected. It should be pointed out that the new instruments have their shortcomings; not all of them live up to their expectations, a situation that is not surprising in any new technology.

One potential problem area lies in overdependence upon the repeatability of the spectral responsivity of detectors. A common practice is to assume that the only significant factor affecting the reproducibility of the detector spectral responsivity is the detector temperature, in which case regulation of the detector ambient temperature would serve to maintain its calibration indefinitely. The constraints that apply to this assumption are in need of clarification. Another significant problem lies in the inadequate attention being given by infrared-radiation-thermometer designers to reducing the size-of-source effect [14], which can lead to very large errors in temperature measurement. Misapplication of measurement technique is also a significant problem, especially where broad spectral bandpass and low target temperatures are involved.

Influence of Radiation Laws in Selection and Application

While misapplication has been a serious and chronic problem in the field of radiation thermometry for many years, the opportunity for misapplication has never been greater than at present, with so many new possibilities [23-26] from which a choice must be made. It is therefore appropriate to examine some of the underlying basic physics of radiation thermometry, together with pertinent characteristics of materials and components available to the instrument designer.

The user is typically confronted with an application in which the temperature, target material, target size, and possibly the response time are already prescribed, as well as the atmosphere lying between the radiation thermometer and the target. The most important parameters to select first are usually wavelength and spectral bandwidth. The reason for this is developed below.

Emissivity Effects. The greatest single problem in radiation thermometry is that no real material radiates as a blackbody. Whereas a blackbody absorbs all radiation incident on it, a real body will reflect some, absorb some, and, if its dimensions are small enough, it will transmit some. This is stated mathematically by the expression

$$\rho_\lambda + \alpha_\lambda + \tau_\lambda = 1 \qquad (7)$$

where

ρ_λ = the fraction of incident spectral radiation that is reflected

a_λ = the fraction of incident spectral radiation that is absorbed

$\mathfrak{I}_\lambda$ = the fraction of incident spectral radiation that is transmitted.

Kirchhoff's law tells us that for thermodynamic equilibrium to be possible

$$a_\lambda = \epsilon_\lambda \tag{8}$$

which, when substituted into equation (7), gives

$$\rho_\lambda + \epsilon_\lambda + \mathfrak{I}_\lambda = 1 \tag{9}$$

Unless specifically stated otherwise, the remainder of this paper will deal with the case where $\mathfrak{I}_\lambda = 0$, i.e., opaque solids and liquids. The temperature of interest will be assumed to be uniform from the surface to a depth at least sufficient to assure total absorption. (This is not strictly valid. At least a small temperature gradient normal to the surface exists when there is a net flow of radiation from the surface.)

In the interior of an opaque body, a photon "sees" itself as surrounded by a perfect absorber, i.e., a photon will be absorbed before it can go very far. Hence, blackbody conditions prevail [27] and the body behaves as if it were filled with blackbody radiation. Very near the boundary, $\mathfrak{I}_\lambda$ cannot be assumed to be zero; however, while the reason is not immediately obvious, radiation arriving at the surface is, in fact, blackbody radiation characteristic of the interior of the body, neglecting the small temperature gradient mentioned above. A fraction ρ_λ of the radiation is internally reflected [28] and the remaining fraction ϵ_λ is emitted, i.e.,

$$\epsilon_\lambda + \rho_\lambda = 1 \tag{10}$$

While the manner of obtaining equation (10) is different than is usually employed, this somewhat mechanistic approach clarifies the relationship between blackbody radiation, spectral emissivity, and spectral reflectance.

By the argument preceding equation (10), it can be seen that the spectral radiance of a real material (nonblackbody) at temperature T can be expressed for perfectly monochromatic radiation as

$$N_\lambda = \epsilon_\lambda N_{b\lambda}(\lambda, T) = N_{b\lambda}(\lambda, T_r) \tag{11}$$

where T_r is defined to be the "spectral-radiance temperature" at wavelength λ.

Selection of Optimum Wavelength. Since the pyrometer measures N_λ rather than $N_{b\lambda}$, it will indicate a spectral-radiance temperature T_r lower than the temperature T by an amount ΔT, such that

$$\frac{1}{T} - \frac{1}{T_r} = \frac{\lambda}{C_2} \ln \epsilon_\lambda \tag{12}$$

Assuming Wien's law to hold, it follows that for moderately small values of ΔT

$$\Delta T \approx -\frac{\lambda T^2}{C_2} \ln \epsilon_\lambda \tag{13}$$

from which the effects of wavelength, temperature, and emissivity on the temperature correction are clearly evident.

It is useful for several purposes to express the function in equation (11) as a power of T

$$N_\lambda = \epsilon_\lambda N_{b\lambda}(\lambda, T) = \epsilon_\lambda \sigma_0 T^n \tag{14}$$

where σ_0 is an arbitrary constant.

Where Wien's law applies

$$n = \frac{C_2}{\lambda T} \tag{15}$$

The influence of ϵ_λ on T may be obtained from equation (14) by differentiation:

$$\frac{dT}{T} = -\frac{1}{n}\frac{d\epsilon_\lambda}{\epsilon_\lambda} \tag{16}$$

From equation (16), to minimize the uncertainty in T, it is necessary to minimize the absolute value of $(1/n)$ $(d\epsilon_\lambda/\epsilon_\lambda)$. In the absence of detailed knowledge of ϵ_λ, it is clearly desirable to have n as large as possible, which requires λT to be as small as possible. Since T has already been presumed to be prescribed, it remains to choose λ as small as possible.

Under some circumstances, $d\epsilon_\lambda/\epsilon_\lambda$ may be known to be so small at some longer wavelength as to override the effect of $1/n$. There are entire classes of materials, such as certain commonly used types of plastics [22, p. 325], that exhibit characteristically high absorption, and consequently high emissivity, in certain spectral regions. This provides a basis for selection of certain wavelengths for common use in radiation thermometry and is discussed by DeWitt and Hernicz [29].

In the case of atmospheric transmittance, the argument is exactly analogous to that for emissivity, and $\mathfrak{I}_\lambda$ replaced ϵ_λ in equation (16). Except under special circumstances then, atmospheric effects are also minimized by keeping λ as small as possible. The presence of atmospheric "windows" and absorption bands gives very pronounced effects in the infrared, Fig. 2.

Influence of Spectral Bandwidth. With the exception of the discussion of the total-radiation pyrometer, the foregoing analysis has made the simplifying assumption that ideally monochromatic radiation is being used. In any radiation thermometer, however, the radiant power received by the detector is dependent upon the spectral bandwidth. For exactly monochromatic radiation, the spectral bandwidth is zero and the detector would receive no radiation. For very narrow spectral bandwidth, the radiant power received by the detector is proportional to the spectral bandwidth; in general, the wider the spectral bandwidth, the greater the amount of radiant power available to the detector.

A moderately high radiant-power input to the detector is generally desirable to maintain a high signal-to-noise ratio from the detector. This permits the resolution of small temperature differences, operation at lower target temperatures, and faster response. It can be accomplished by using a wide spectral bandwidth, a very common practice, especially in the manufacture of inexpensive radiation thermometers. However, the use of a wide spectral bandwidth tends to degrade the accuracy and repeatability of radiation thermometers, and should be undertaken with due caution.

For linear detectors (in which the signal output is directly proportional to the radiant signal input) of the types ordinarily used in radiation thermometers, the signal generated by the detector is described as in equation (5)

$$S(T) = \Omega A \int_0^\infty \epsilon(\lambda)\mathfrak{I}_a(\lambda)N_b(\lambda, T)\mathfrak{I}_o(\lambda)R(\lambda)d\lambda \quad (17)$$

where Ω is the solid angle of target radiation received at the detector and A is the detector area. $\mathfrak{I}_o(\lambda)\ R\ (\lambda)$ is zero for all values of λ except those in the passband between λ_1 and λ_2, so the upper and lower limits of the integral may be replaced by λ_2 and λ_1, respectively. In interpreting the detector response, it must be recalled that the signal $S(T)$ is originally calibrated with reference to a blackbody for which the temperature is assumed to be known over the range of interest, under conditions in which $\epsilon(\lambda)$ and $\mathfrak{I}_a(\lambda)$ are taken to be unity. When the radiation thermometer is used to measure the temperature T of a heated surface having a spectral emissivity $\epsilon(\lambda)$ through an atmosphere having a spectral transmittance $\mathfrak{I}_a(\lambda)$, it will respond with a signal $S(T_r)$ as if it were sighted on a blackbody at a lower spectral-radiance temperature T_r in the absence of the perturbing atmosphere, i.e.,

$$S(T_r) = \Omega A \int_{\lambda_1}^{\lambda_2} \epsilon(\lambda)\mathfrak{I}_a(\lambda)N_b(\lambda, T)\mathfrak{I}_o(\lambda)R(\lambda)d\lambda \quad (18)$$

$$= \Omega A \int_{\lambda_1}^{\lambda_2} N_b(\lambda, T_r)\mathfrak{I}_o(\lambda)R(\lambda)d\lambda \quad (19)$$

The theory of narrow-spectral-bandwidth optical pyrometry is fully developed, as discussed by Kostkowski and Lee [3], in terms of the mean effective wavelength $\lambda_e(T, T_r)$ on the assumption that at least the relative value of the product $\epsilon(\lambda)\ \mathfrak{I}_a(\lambda)$ is known. (In optical pyrometry $\mathfrak{I}_a(\lambda)$ is usually assumed to be unity.) The mean effective wavelength is defined to be that wavelength (or those wavelengths) for which the integrands in equations (18) and (19) have the same value. Since the integrands may be removed from the integral and equated at λ_e, it follows that

$$\epsilon(\lambda_e)\mathfrak{I}_a(\lambda_e)N_b(\lambda_e, T) = N_b(\lambda_e, T_r) \quad (20)$$

Assuming the applicability of Wien's law, equation (2) may be substituted into equation (20) to give

$$\frac{1}{T} = \frac{1}{T_r} + \frac{\lambda_e}{C_2} \ln\left[\epsilon(\lambda_e)\mathfrak{I}_a(\lambda_e)\right] \quad (21)$$

To determine the temperature T from the measured spectral-radiance temperature T_r, it is seen from equation (21) to be necessary to know the value of λ_e, as well as the value of $\epsilon(\lambda_e)\mathfrak{I}_a(\lambda_e)$. From equations (18) and (19) and the definition of mean effective wavelength, it is clear that the value (or values) of λ_e depends on the functional form of $\epsilon(\lambda)\mathfrak{I}_a(\lambda)$, as well as on the two temperatures T and T_r. The functional form of $\epsilon(\lambda)\ \mathfrak{I}_a(\lambda)$ is strongly affected by atmospheric absorption in the infrared and may vary greatly as a function of wavelength, both with absolute humidity and with distance between the radiation thermometer and the target. For the mean effective wavelength to be well defined it is necessary either to restrict the spectral band to one of the "windows" in the atmosphere, Fig. 2, where the transmission is very nearly unity and is independent of wavelength, or to use a sufficiently small distance that atmospheric absorption can be assured to be negligible. This assures that the measured spectral-radiance temperature will be a function only of properties of the target, $\epsilon(\lambda)$ and T, and not of the atmosphere.

Equation (21) is not often used in its exact form in common applications, even when the spectral emissivity is known, since to do so would require a tedious numerical integration of equations (18) and (19). It is common practice to determine λ_e only for the case in which the target is a blackbody, since this can be done by the manufacturer and is usually valid for the life of the instrument. That value of λ_e is then used in equation (21), together with the spectral emissivity at the same wavelength. Both λ_e and $\epsilon(\lambda_e)$ are then approximate values that approach their true values as the spectral bandwidth becomes narrow. For a broad bandpass, the approximation may be so poor as to become essentially meaningless; one then ordinarily resorts to an empirical calibration such as is done with total-radiation pyrometers, equation (6).

It is to be concluded that the spectral bandwidth should be kept as narrow as the available radiant energy permits, and care should be exercised to avoid spectral regions likely to be influenced by atmospheric absorption. Similarly, a spectral region in which the spectral emissivity tends to be high and constant, both as a function of time and of wavelength, is to be preferred.

Combinations of Atmospheric Windows and Detectors Suitable for Common Use. An examination of Fig. 2 reveals a group of "windows" in the atmosphere, i.e., spectral regions in which the atmosphere is highly transparent under ordinary conditions. One such window exists throughout the visible spectrum, where photomultipliers are generally applicable. One near 1 μm is conveniently located with respect to the optimum response region for silicon detectors. Another, which somewhat surprisingly does not seem to have found much application as yet, is in the neighborhood of 1.6 μm, where intrinsic photoconduction in germanium is very good. A fourth and especially significant region is from about 2.0 to about 2.4 μm, where lead sulfide is near optimum. A fifth region is from 3.4 to 4.2 μm in which a filtered indium arsenide, lead selenide, or mercury–cadmium–telluride detector could be used. A region from about 9.5 to about 11.0 μm is especially transparent, and can be used with a filtered thermal detector. There are various other narrow windows that can be employed for special applications, since it is possible to use optical filters of narrow spectral bandwidth. Strong absorption bands due to water vapor and carbon dioxide preclude use almost entirely from 2.6 to 2.8 μm, from 4.2 to about 4.4 μm, and especially from 5.5 to about 7.3 μm, unless special precautions are taken to remove these gases.

Subsurface Temperature Measurement in Partially Transparent Media. It was assumed, in going from equation (9) to (10), that the material whose temperature is to be measured would be taken to be sufficiently thick that it could be treated as opaque. For good electrical conductors such as metals, only a very small depth is required to achieve this condition. For a partially transparent medium exhibiting selective absorption (such as glass or plastic), however, the requisite depth to achieve essentially total absorption varies with wavelength. By careful selection of wavelength, it is possible to infer the temperature of the material at depths that are a function of the selected wavelength. The problem is made significantly more complicated by the presence of temperature gradients and scattering characteristics within the material. The theoretical treatment of the problem was initiated by McMahon [30] and Gardon [31] and a summary of the historical development and present status [32] of the theory was recently given by DeWitt and Hernicz [29].

Detector Stability. Warnke [23] has made a qualitative comparison of the suitability of various detectors for radiation thermometry in terms of their stability. Silicon was the only one stated to be suitable for use in the d-c mode (other than thermal detectors, for which the response time is generally inconveniently long for chopping), and it required compensation for ambient-temperature variations. The other detectors all had to be operated in the a-c mode using chopped radiation input to avoid d-c drift problems, and all required compensation for ambient-temperature variations. Lead sulfide was described as being so unstable that it should not be used without a quick and convenient means of calibration such as a built-in lamp or blackbody source.

Warnke's appraisal was under the assumption that the detector itself would be calibrated, and did not apply to the detectors when used as null detectors. When used as null detectors, the key factors are the detectivity and the response time. With respect to response time, all of the "quantum" detectors are very fast, ranging from less than a microsecond for InSb to about a millisecond for PbS. "Thermal" detectors, including thermistor bolometers and thermopiles, have response times generally of the order of a few milliseconds to a second or more.

Values of spectral detectivity D^*_λ for various infrared detectors currently of interest to infrared-radiation thermometry are shown in Fig. 4. Only detectors suitable for operation at room temperature, i.e., with the detector itself at room temperature, are shown, but only because the expense and inconvenience of application of cryogenically cooled detectors has, to date, precluded their widespread use in radiation thermometry. It appears highly likely that applications will develop where the additional expense and inconvenience are justified, and it is probably only a matter of time before cryogenically cooled detectors are optionally available for a variety of radiation thermometers.

Values of D^*_λ are not shown in Fig. 4 for detectors operating in the visible and ultraviolet spectrum, where photomultiplier tubes are most commonly used. Photomultipliers have spectral detectivities typically about two orders of magnitude higher than the highest shown in Fig. 4. They may be used to considerable advantage for high-temperature targets, where sufficient radiant power is available to permit use of a shorter wavelength. Above about 1000 C, photomultipliers are likely to be a better choice than infrared detectors.

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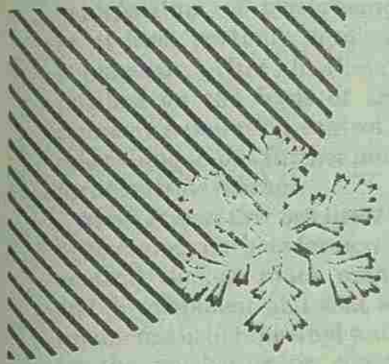
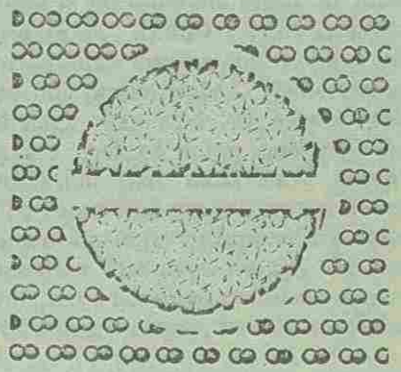


PITFALLS & PROFITS



In recent years, environmental mangement has been a popular business for actual and contemplated diversification. But there are a number of problem areas confronting prospective new entrants into this growing market. Here's a timely look at the existing dangers as well as the opportunities that they will face.

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By now companies which have entered the environmental management business and most of those which have watched it with interest have discovered that its profitability and growth have not been equal to the promises implicit in its press. Certainly, the national pollution problem has not been brought under control as yet, and it is not going to be solved very quickly in the future. On the other hand, it is just as certain that social concern for a better environment is not going to dissipate like last year's fad. There may be temporary lapses in the pressure for the abatement of pollution. There may be periods of reaction because of heavy costs and sacrifices required to fulfill environmental programs, but the emphasis should return as in a series of heartbeats and continue until the situation is finally under control.

Meanwhile, some common dangers have become apparent for the entrant into the pollution control market. Directions for more profitable participation are also becoming clear. Pitfalls and opportunities in six areas of activity are discussed here and summarized in Table 1.

Where Are the Pitfalls. . .

. . . in the Nature of Control Problems?

Defining Pollution. We are still searching for a better definition of pollution and for a better process of identifying specific pollutants. Even if a general definition of pollution were adopted, the actual identification of pollutants would still be inhibited by our ability, or inability, to scientifically understand their full effects or to prove their negative impact.

Changing Standards and Criteria. Markets in environmental management will not truly blossom until the pollution laws that are now on the books at least begin to become enforced. Enforcement, on the other hand, requires that sufficient criteria and standards by which to measure, judge, manage, and control pollution be established. Customers for pollution control systems will be hesitant to purchase proper equipment until the standards of enforcement are known. Those standards are difficult to establish until there are better criteria by which to measure pollution control or define a desirable environment. These criteria, in turn, cannot be fully developed until realistic priorities are placed upon health, conservation, economics, and aesthetics. Finally, these criteria cannot be clearly defined until further research has outlined the nature of contaminants, the means by which to measure them, and the techniques by which to control them.

. . . in Commercializing the Product?

The Home-Grown Product. A natural phenomenon of the evolving pollution control business has been the development of new products and procedures by manufacturing companies to solve their own pollution problems. The danger point in this natural corporate process does not lie in assignment of these problems to internal engineering staffs, because they are often the ones who are in the best position to solve those problems. The danger, however, lies in overestimating the competitive capabilities of the system that has been de-

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Based on a paper contributed by the ASME Management Division.

veloped, the generality of its application, and the ease with which the system could be sold to outside parties.

The first question that must be asked of an internally developed system is just how it compares to systems already in the marketplace. One should not underestimate the psychological investment which internal inventors have with their device or system. The environmental field has been well trained to suspect claims made for control systems which are as yet unproven. It is important to insure that internally developed systems are fully tested and that the theoretical extrapolation of performance to similar installations be at least partially verified before commercialization is pursued. After all, these systems can be internally justified on the basis of the savings they lend to a company's pollution control problems. It is quite another thing to put further money into their development for an outside market.

Does a Product Ever Sell Itself? It is one of the curiosities of emerging markets for new technologies (like pollution control) that so much money is invested in research and development and that so little is often devoted to commercializing the final product. For those who work on the marketing or commercial development side, this irony is all too clear. For those who are on the research and development side, it is wise to review the other side of the picture. In marketing to the environmental management business, the mistake of underestimating the relative importance of marketing may be critical. In markets calling for new technologies, the importance of having a good product is, of course, paramount. Without a good or superior product, a new entrant into the business is at a serious disadvantage. Without at least a competitive sales effort, successful new entry is simply not possible.

. . . in the Character of Customers?

Another Cost of Doing Business. One of the first changes implied in the pollution control movement that had to be accepted was that it was going to be necessary despite the fact that there is no inherent profit in most pollution control situations. Industry is not used to putting monies, particularly investment monies, into endeavors that are not profit-related. Whereas general corporate psychology was slow to accept pollution control as a future cost of doing business, there is considerable indication that most have accepted it by this time. To those who are interested in entering the pollution control business with profitable products, it is good to remember that even though the customer may, by this time, have accepted pollution control as a legitimate cost of doing business, he still thinks of it as nonproductive.

Municipal versus Industrial. If pollution markets were defined to include at least air pollution control, water and waste treatment, and solid waste management, the bulk of the monies spent in these areas would lie in municipal or municipally related markets. Solid waste management is largely a business of municipal

TABLE 1 Summary of Problem Areas and Areas of Opportunity in Entering the Environmental Management Business

Areas	Problems or Pitfalls	Opportunities for Profit
A) Problem-related	Identification of pollutants Definition of criteria Setting of standards	Developing methodologies and technologies to solve problems of pollution control
B) Product-related	Comparative performance Proprietary advantage Professional credibility	Documentation of performance in comparison to competitive devices
C) Customer-related	A cost of doing business Municipal versus industrial Specialty versus full service	Attention to the special needs of each customer group
D) Market-related	Product visibility Customer specialization Heavy marketing investment	Commitment to an expensive effort in marketing and technical backup
E) Competition-related	Strengths of current suppliers Strengths of future suppliers R&D suppliers	Intelligence on the complete and market strengths of existing and potential competition
F) Timing-related	Mixed legislative record Mixed enforcement record Availability of monies	Sensitivity to the dynamics of society, ability to tolerate and the polluter's ability to pay

trash collection and disposal. Total expenditures for water and waste treatment still include a majority of municipal monies for water and sewage treatment facilities. Air pollution control, on the other hand, is primarily an industrial market, but one segment of it—the electric power industry—is closely related to municipal services.

This large municipal or public-sector market is important to an understanding of the problems of entering the environmental management field. Those companies which have not served municipal markets in the past may either be unaware of the requisites of serving that market or dedicated to staying at arm's length from it. The realities of the municipal marketplace may be a major hurdle for a new entrant into the business, but avoiding the municipal market removes a large potential from an environmental management venture. In short, municipal markets are often larger but usually less profitable than industrial markets.

Specialized versus Full-Service Customer Needs. There has been a growing trend toward the provision of a full line of products and services, or a "systems capability," to the environmental management business. This trend reflects the frequent need of municipalities and industry for assistance in understanding the newer pollution control problems and the range of alternative measures for their solution. In municipal markets, this need is met to a large degree by the reliance of municipalities upon the advice of consulting engineering firms. The consulting engineering firms, in turn, draw upon manufacturers for particular components of an overall system design.

To better understand the impact of a need for full service at this time and to understand the probable development of the market in the future, it is also well to watch another development in the industrial market. Particularly in these times when the central engineering staffs are low on work there is a growing drive to self-sufficiency in industry with regard to its own pollution problems. Thus, many companies already have capabilities to analyze their pollution control needs, to design a capable control system, and to define equipment specifications.

In terms of profitability, there are many differences between a specialized-entry approach versus a broad-product-line and systems approach to the market. In most markets, the profits associated with specialty products are usually higher. In the environmental-management business, the same is true. Often, however, more profits may come from the provision of associated services than from the sale of traditional hardware, providing those services require a broader product line from which to solve the customer's problems. Although this approach may involve a number of products of marginal profitability, the overall value of providing a full product line and systems capability may justify it.

. . . in the Marketing Process?

Product Visibility. The environmental management marketplace has what might be termed a "high noise level." Products now available on the marketplace are traditional technologies typically sold as off-the-shelf equipment by established companies. As technologies are traditional and differences between competitive products are small, the differences that do exist tend to become exaggerated. As a result, a new entrant into the business, who has an honest improvement over existing pollution control systems, cannot be assured that the advantages of his system will be recognized in the din of competitive claims.

No pollution control system has been known to sell itself. In addition to contending with the high pitch of competitive claims, the new producer must convince experienced practitioners in the field who have learned to be suspicious of any new system which claims substantial improvement over existing systems. To deal with the promotional noise level, the new supplier must persevere in getting his message through to the customer and adorn his marketing pitch with substance, e.g., actual facts and figures on performance. To achieve credibility, the new supplier must endeavor to prove his system's capabilities to a skeptical professional community. In short, this marketing process takes considerable time, money, and effort.

Whence the Right Staff? One alternative to entering the environmental management business is to develop both technical and marketing capabilities internally. If the effort is already built on internal product developments, then the core for a technical effort is already in-house. The major problem then lies in finding the right people to commercialize the venture. If the corporation has "psychological" problems with adjusting to the differences between its present business and the environmental management business, then the commercialization alternatives include licensing, joint venture, or acquisition. Licensing obviously leaves a corporation more out of the business than in it with only a token realization of profits and relationship with the final market. Joint venture, while offering the potential benefits of complementary corporate capabilities, does involve the difficulties of agreeing on mutual goals between venture partners and limiting the horizons of individual efforts in the future.

Acquisition in the environmental management business requires a selective search for attractive companies from a list which has already been heavily picked over. There is a special problem of accommodating the kinds of organizations which are now in the environmental business with those which are typically considering entry into it. For the very reasons that acquisitions seem attractive, there are associated problems. While the marketing intelligence of existing companies may be their attraction, their lesser experience with research and development carries with it an implicit difference in staff and attitudes. These differences offer serious problems to a corporate marriage. Also, the addition of marketing intelligence or product lines through acquisition is primarily a means of buying time, and the benefits therefrom are temporary compared to the alternative of internal development. With the environmental management business thus far, buying time has not been all that important, but it may be more critical now.

. . . in the Character of the Competition?

Their Weaknesses and Strengths. As already noted, the traditional strengths of existing companies in the environmental management business lie in their knowledge of the problems of their customers, their personal familiarity with purchasing and engineering staffs, and their ability to adapt a piece of off-the-shelf equipment to a specific situation. Typical weaknesses of these companies lie in their financial resources, their research and development activities, and their capability for developing new technologies needed to control pollution. To meet these competitors, the new entrant must challenge their marketing prowess and at least equal their technical-product systems. To beat them, one must have a superior product and at least equal their marketing capabilities.

Emerging versus Entrenched Companies. The new entrant is also advised to keep his competitive eyes on other companies that can be expected to enter this business in the future. Thus, what may appear to be a competitive advantage now may become less of an advantage as more companies enter the marketplace. Thus, the foregoing description of typical advantages and disadvantages of the new entrant is a transitional one depending upon the inroads made by newer and more technically based competitors.

. . . in Timing?

The Legislative Record to Date. In reviewing pollution regulation in this country, one must remember that until 10 years ago the existence of a pollution parameter in corporate decision-making was unknown. Similarly, the governmental machinery necessary to understand, regulate, and enforce pollution control was practically nonexistent. What has been seen is the development of a completely new governmental system to handle an entirely new social issue in a very short time. If there has been a large amount of inefficiency, repetition, and mistaken management in the effort, it must be understood in this light.

While that is not an excuse for misspent monies, ill-advised laws, and short-sighted regulation, such problems will continue as the pollution effort both broadens and draws closer to enforcement. There has been a shortage of knowledgeable manpower to administer these laws in the past, and there will be so for some time. There has also been a lack of understanding of the nature of pollution, a lack of the ability to pay for the control of it, and a lack of the political sense needed for effective enforcement—conditions that will continue to impede progress in the future.

There are hopeful signs that at least one aspect of the situation is beginning to change. As in any new area of social concern, the earlier years are characterized by exaggerated positions on either side. Thus, conservation-minded prophets and industry apologists have exhausted much of their usefulness. There is a growing awareness of both the need to do something about pollution and the high social cost involved in controlling it. With more intelligent appreciation of these practicalities by both sides, improved legislation, more sensitive enforcement, and more responsible pollution control practice is beginning to develop.

Where Might the Profits Be. . .

. . . in Solving Pollution Problems?

There are many pollution problems for which there are no satisfactory answers. Major efforts are underway to solve them, and some candidate technologies are now apparent. This does not contradict the common observation that the technology to handle most of our current pollution problems is available and that the limiting factors are manpower, organization, and economics. With the reminder that no new technology will sell itself and that performance has to be proved, the development of a new technology to handle unsolved pollution problems is a leading avenue to profits.

. . . in Documenting Product Capabilities?

What traditional suppliers in this business typically lack is a healthy development budget. It is this disadvantage of present suppliers that new entrants can capitalize upon with their own technical sophistication. To the degree that a new supplier can develop new technologies, can document performance, and can implement successful application, the profits usually associated with quality products and quality backup may be realized.

. . . in Matching Customer Needs?

As in most industrial-service markets, a profitable route to proprietary advantage is to develop a strong marketing sensitivity to the specific application problems of customer industries. It is in this area of customer service and intelligence that the present suppliers of pollution control products enjoy their market leverage, and it is in this area that new entrants can also achieve profitable participation.

. . . in Acquiring Marketing Competence?

As successful market penetration cannot be assured by a good product alone, profitable participation in the environmental management business is probably foreclosed without informed marketing intelligence. The sources of this intelligence may lie in a company's internal knowledge of its own industrial processes, in the hiring of personnel with background in the environmental management business, or in the acquisition of companies with established market ties.

. . . in Exploiting Competitive Intelligence?

In addition to the development of a good product and the development of an informed sales staff, another tool for building a successful pollution control venture is a strategic study of competition. After the new entrant has done his homework on the relative strengths of his intended competition, he can then better maximize his own thrust in the marketplace by following competition into proven markets which are profitable (and which can stand another supplier), by outflanking competition into new areas of opportunity, by exploiting relative corporate strengths, and by matching competition in areas where head-to-head conflict is inevitable.

. . . in Being Ready at the Right Time?

At the rate that the pollution control movement threatens to accelerate, it has been the concern of many that it is too late to begin an effective drive into this marketplace. As national progress has not kept up with national ambition, however, it is not yet too late. There is still time to take the time to do it right.

Avoiding the Emissivity Problem

radiation thermometry

Here's a look at some recently developed techniques that compensate for unknown variations in emissivity, removing such effects as a source of error in radiation thermometry.

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It is common practice in industrial radiation thermometry either to use the radiance temperature without correction, or to apply a correction for a measured or assumed value of emissivity applicable to the problem at hand, Fig. 6. Special filters are available for optical pyrometers to make them "direct-reading" for materials having a spectral emissivity of about 0.4 at 0.65 μm. These are especially convenient in certain steel-mill applications. Most other types of automatic pyrometers discussed in Part 1 provide an adjustment for emissivity to make the instrument direct-reading, assuming that the emissivity is known.

Although useful emissivity data are often difficult to obtain, the heat-transfer problems associated with the exploration of space caused the generation of a large quantity of such data. A special project has been undertaken at the Thermophysical Properties Research Center at Purdue University to critically evaluate and catalog as much of that and other related data as possible. The data thus generated for radiative properties, such as emissivity, have just begun to become available [29, 33–35][2] and should be of considerable aid to those involved in applied radiation thermometry. However, while data from the literature can be a useful guide, they are often little more than that, and from the viewpoint of applied radiation thermometry, the "emissivity problem" remains a very thorny one.

Simulated Blackbodies

The most certain method of avoiding the problem of emissivity effects is to create a cavity in the surface of the target, the shape and dimensions of which can be designed to give an effective emissivity of very nearly unity. This is a nearly ideal solution where the method is applicable; unfortunately, in most instances of industrial interest, it is not, although it is common practice in research and development laboratory applications. Because of their fundamental importance in thermal-radiation physics, the design and effective emissivities of blackbody cavities have received considerable study in the past few years. A substantial body of useful literature is now available, recently reviewed by Bedford [36], in which the effective emissivities of a number of cavity geometries of interest in engineering applications have been well established. Although most studies assume perfectly diffuse interior surfaces, effective emissivities have also been calculated for some cavities having specular surfaces.

Ratio Pyrometers

A second method that has been used extensively with limited success [26, 37–39] is that employed by the "ratio pyrometer." In the ratio pyrometer, the assumption is made that the target has the same emissivity at two wavelengths. The radiance ratio R is then measured at those two wavelengths and is a

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Based on a paper contributed by the ASME Research Committee on Temperature Measurement. This survey was based on work supported by the Pyrometer Instrument Co., Inc., Northvale, N. J.

[2] Numbers in brackets designate References at end of article as well as References at end of Part 1 of the article.

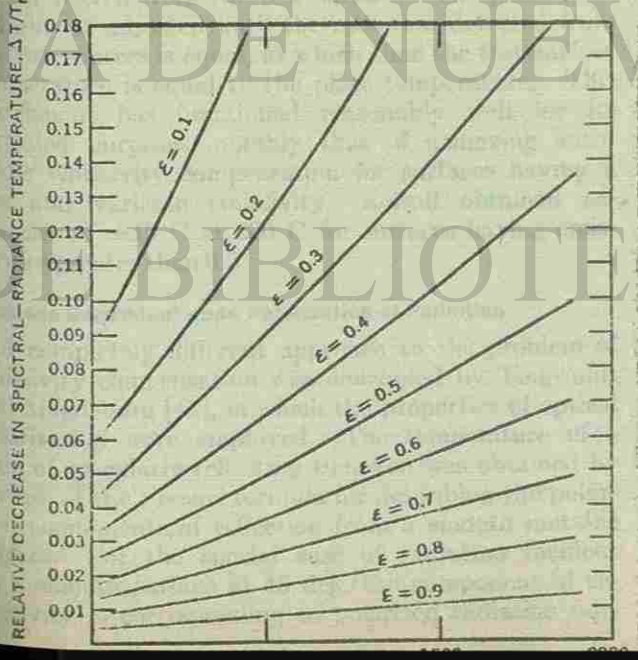
Part 2—Solving the Emissivity Problem

function of the temperature of the target.

$$R = \frac{\epsilon(\lambda_1)}{\epsilon(\lambda_2)} \left(\frac{\lambda_1}{\lambda_2}\right)^{-5} e^{-\frac{C_2}{T}\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)} \qquad (22)$$

If the two emissivities have the same value, $\epsilon(\lambda_1)/\epsilon(\lambda_2)$ cancels out in equation (22) and the ratio is independent of the emissivity. If the emissivity ratio is different from unity (it usually is at least somewhat different), the resulting error tends to be large. If the two spectral bandwidths are not narrow, the effective wavelengths λ_1 and λ_2 are not well defined, and any error in the wavelength ratio is magnified because of its large exponent. The temperature indicated by this kind of pyrometer is called a ratio temperature, and it assumes equal spectral emissivities. If the emissivity ratio is sufficiently reproducible, it may be "calibrated out" of the instrument reading. Ratio pyrometers are inherently less sensitive than monochromatic pyrometers, so their application tends to be at the higher temperatures. In spite of its limitations, the method has found some practical application in the steel industry [39]. Errors in ratio pyrometers have been discussed by Emslie and Blau [37], Pyatt [38], and Ackerman [26].

Fig. [illegible] Effect of spectral emissivity. Relative amount by which the observed spectral-radiance temperature T_r has been reduced by the effect of spectral emissivity presented as a function of λT_r. Values are based on exact computation from the Planck radiation distribution.



Reflecting Hemispheres

A method developed by Land and Barber [40], and improved by Pattison [41], consists of covering the heated surface with a highly reflecting hemisphere. Multiple reflections within the hemisphere increase the radiance of the surface such that radiation emerging from an aperture in the hemisphere is nearly blackbody radiation. Of all available methods of radiation thermometry other than the use of blackbodies, this method is generally the least influenced by the presence of extraneous radiation. For surfaces having a low thermal conductivity, however, there is a slight change in surface temperature (when the hemisphere is in place) because the hemisphere changes the irradiation on the surface. When applied to a diffuse surface of spectral emissivity ϵ_λ, the effective emissivity of a circular aperture of diameter d in a truncated hemisphere of radius r can be calculated exactly, Fig. 7. Assuming that the hemisphere has an internal spectral specular reflectance ρ_λ, and has its center on the heated surface and its edge a distance S above the surface, the circular aperture viewed along an axis through the center of the hemisphere will have an effective spectral emissivity

$$\epsilon_{\lambda_{\mathrm{eff}}} = \frac{\epsilon_\lambda}{1 - (1 - \epsilon_\lambda)\rho_\lambda(1 - F)} \qquad (23)$$

where

$$F = \left[2\left(\frac{S}{r}\right)^2 + \frac{1}{4}\left(\frac{d}{r}\right)^2\right] \qquad (24)$$

Reflection of Radiation from a Heated Source at Known Temperature

A method that is similar in principle (use of reflected radiance to develop the appropriate blackbody radiance from a specular surface) has been described by Fastie [42] and by Tingwaldt [43]. In this method, the radiation from a blackbody is reflected from the heated specular surface. The sum of the reflected blackbody radiation and that emitted by the specular surface is then measured. When the temperature of the blackbody is adjusted to be equal to that of the specular surface, the radiance of the blackbody is the same as the reflected plus emitted radiance of the specular surface. This method, aside from its inconvenience, suffers somewhat from the requirement for a high degree of specularity. It does not work particularly well for specular surfaces of low emissivity when the radiance of the blackbody is the dominant component measured by the radiation thermometer.

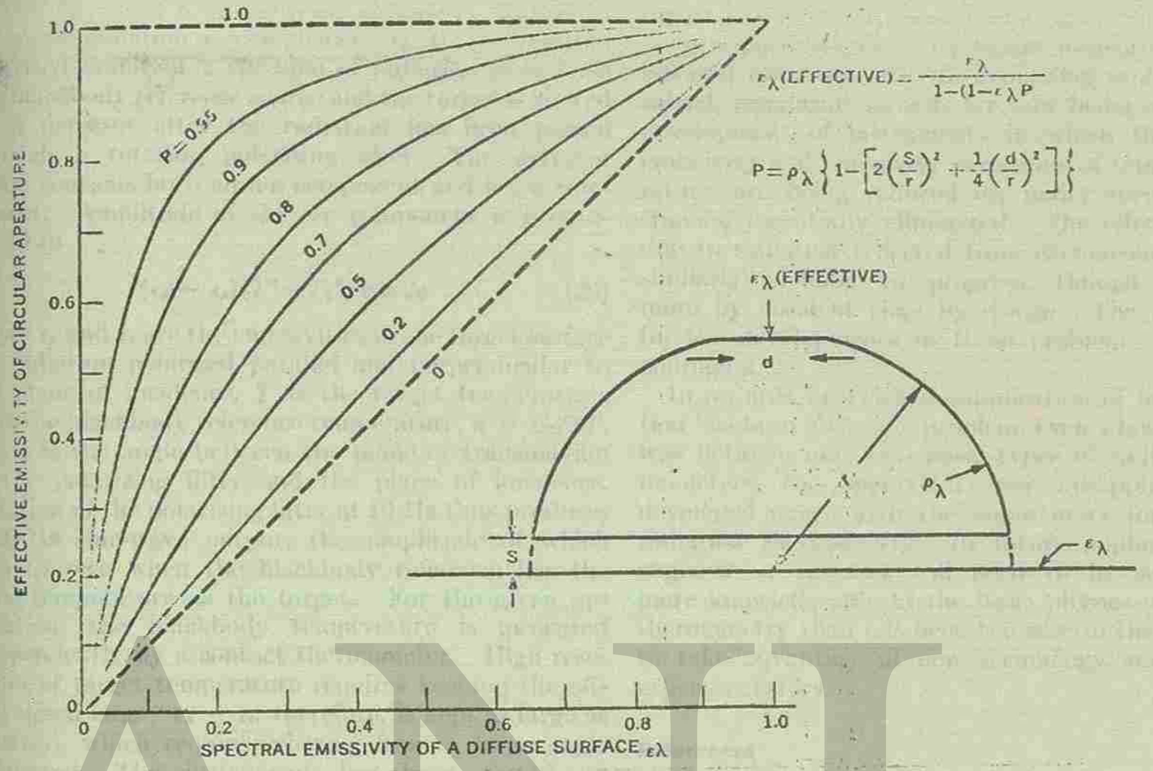


Fig. 7 Effective emissivity is enhanced by multiple reflections from a hemispherical mirror.

High accuracy is needed in the radiance comparison to avoid significant errors under those conditions.

Another method that is similar in principle to those described in the foregoing has been reported by Kelsall [44]. In this method, a heated plate is placed just above the test surface (2 to 5 cm distance), and a radiation thermometer (PbS detector in the case cited) compares the radiation from a region on the upper surface of the reference heater with the radiation from the lower surface of the reference heater after it has been reflected from the test surface. The plate temperature is adjusted until the radiation detected from the two sources is equal, at which time the test-surface temperature is equal to the plate temperature. This instrument has functioned reasonably well for its intended purposes, notably that of achieving automatic emissivity compensation for surfaces having a low and variable emissivity. Kelsall obtained accuracies of ±10 C at 200 C for surfaces having emissivities greater than 0.2.

Methods Dependent upon Polarization of Radiation

A completely different approach to the problem of emissivity compensation was developed by Tingwaldt and Magdeburg [45], in which the properties of optical polarization were employed. The temperature of a strip of specularly reflecting tungsten was obtained by the use of the Fresnel formula for describing the polarized components of reflection from a smooth metallic surface. For the special case of radiation incident on a smooth surface at 45 deg, the component of reflectivity ρ_s corresponding to polarized radiation normal to the plane of incidence and the component ρ_p parallel to the plane of incidence are related by

$$\rho_p = \rho_s^2 \qquad (25)$$

Using a narrow-spectral-bandwidth radiation thermometer with a polarizing filter, the ratio of $N_p(\lambda, T)$ to $N_s(\lambda, T)$ was measured, from which a value was calculated for the spectral emissivity. From a direct measurement of the spectral-radiance temperature T_r from the same position and from the relationship $N_b(\lambda, T_r) = \epsilon_\lambda N_b(\lambda, T)$, the temperature T may thus be determined.

It was necessary to exclude extraneous radiation in this measurement, and high accuracy was required in the measurement of radiance. Tingwaldt and Magdeburg obtained values of $\epsilon(\lambda)$ from several measurements in which the deviation among the values was not more than 1 percent, and for which the mean values agreed well with the best available data from other sources, falling between values found by DeVos and Larrabee.

In a more recent development, Murray [46] has applied a variation of the polarization method to materials having diffuse surfaces. While succeeding to a high degree in achieving a radiation thermometer whose readings are independent of the target emissivity, the system, as presently used, requires close proximity to the target. It also shares the characteristic of the Tingwaldt and Magdeburg approach in that it depends on viewing the target from a direction in which the emitted radiation is polarized, but is not restricted to the 45 deg angle. Unpolarized radiation emitted by a [illegible] is polarized at least to some extent upon [illegible] from the somewhat diffuse target surface. [illegible] component is therefore somewhat [illegible] radiation. Reflected polarized radiation is complementary to the emitted polarized radiation. The sum of radiation from both the blackbody reference source and the target is viewed by a detector after the radiation has been passed through a rotating polarizing filter. The detector signal contains both an a-c component and a d-c component. Amplitude of the a-c component is proportional to

$$(\epsilon_p - \epsilon_s)(T^n - T_b^n) \cos 2\phi \qquad (26)$$

where ϵ_p and ϵ_s are the emissivities of the target surface for radiation polarized parallel and perpendicular to the plane of incidence, T is the target temperature, T_b is the blackbody reference temperature, $n = C_2/\lambda T$, and ϕ is the angle between the plane of transmission of the polarizing filter and the plane of incidence. Rotation of the polarizing filter at 10 Hz thus produces a 20-Hz sine-wave output, the amplitude of which goes to zero when the blackbody reference has the same temperature as the target. For the given application, the blackbody temperature is measured independently by a contact thermometer. High resolution of target temperature requires keeping the off-null signal large; $\epsilon_p - \epsilon_s$, therefore, is kept as large as practical, which requires viewing from a large angle off-normal. The instrument has been tested on materials with varying surface finishes and with emissivity ranging from 0.05 to 0.47, with a mean error of about ±2 percent of the absolute temperature, over a temperature range from about 150 to 450 C. Geometry-dependent systematic errors of a few degrees are not presently well understood and are under study.

Measurement of Absorptivity Ratio

Another method recently reported for reducing errors due to emissivity effects is a new approach by DeWitt and Kunz [47], who combined radiance temperatures measured with two monochromatic-radiation thermometers operating at different wavelengths with a measured value of the emissivity ratio at those two wavelengths. This is done by irradiating the target with lasers operating first at λ_1 and then λ_2, and measuring in each case a momentary increase in target temperature at a third wavelength. The assumption is then made that the ratio of the increase in target temperature, measured in a third spectral region and corrected for the laser power ratio, is equal to the ratio of the absorptivities at the two wavelengths λ_1 and λ_2, and hence to the ratio of the two emissivities. The method has only been applied to thin-tungsten-strip lamps, where a significant temperature rise could be obtained, and it remains to be determined to what extent the method is applicable to thick pieces of material. A related method involving the measurement of the spectral-reflectance ratio at two wavelengths also shows promise and has been summarized by Bramson [48].

Conclusion

It is apparent that under the influence of changing technology, over the past 10 to 15 years radiation thermometry has undergone a renaissance that is still in progress in terms of automation and achieving higher accuracy; a considerable amount of effort is being applied to lower-temperature measurements using infrared radiation. Of the remaining problems to be solved, significant inroads are now being made in the development of instruments in which the effect of emissivity and emissivity variations of unknown magnitude are being reduced or, under special circumstances, essentially eliminated. The effect of errors due to radiation reflected from extraneous sources is similarly yielding to progress, though apparently more by accident than by design. The outlook for further developments in these problem areas is encouraging.

In an area in which misapplication of instrumentation has been a chronic problem, even when the choice was between only two basic types of radiation thermometers, the opportunity for misapplication has developed apace with the opportunity for improved radiation thermometry. In future applications, the engineer or scientist will need to be substantially more knowledgeable in the basic physics of radiation thermometry than has been the case in the past, both to take advantage of new technology and to avoid expensive errors.

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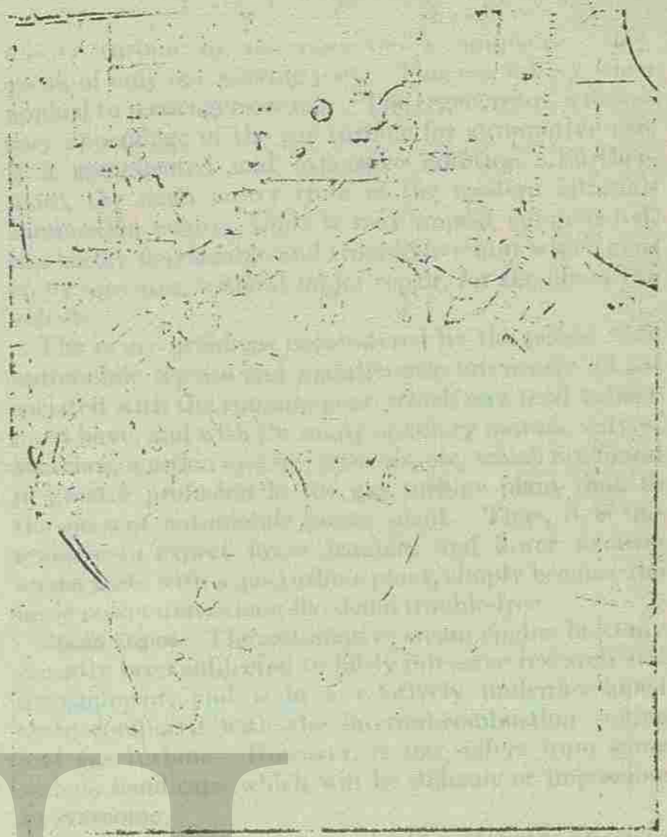
engine and the environment



Ten years from now, at least 100 million more I-C engines will have been built. Pending the development of a substitute, a radical change in engine design is imperative if atmospheric pollution is ever to be cleared up. This should be one of the goals of future versions of the Clean Air Act.

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THE IMAGE of the internal-combustion engine has changed in recent years from that of a benefactor of mankind to a major villain in the ecological wars. But since this engine powers most of the movement of goods as well as people—railroads, trucking, inland marine, much ocean shipping, and the movement of fluids through pipelines—eliminating or even seriously curtailing its use cannot even be contemplated until adequate substitutes have been provided.

Possible Substitutes

The set of possible substitutes for the conventional automobile engine is relatively large, and all of its members have been looked at with varying degrees of effort and intensity. The set includes, among others, continuous-combustion engines following the Rankine (steam engine), Brayton (gas turbine), or Stirling cycles; electric drives powered by batteries, fuel cells, or more exotic thermoelectric, photovoltaic, or thermionic devices; and various hybrids involving combinations of two or more individual systems.

The Department of Health, Education and Welfare, through the National Air Pollution Control Administration, has funded several studies to examine comprehensively and evaluate possible alternative power systems, to identify those that hold the most promise, and to make recommendations concerning additional needed research and development. Kirk and Dawson[2] summarized these studies as well as those of other government agencies and industrial laboratories in a paper presented at the 1969 Winter Annual Meeting of ASME. They identified the most promising possibilities for various classes of vehicles, but indicated that for passenger-car use only the steam engine, gas turbine, and high-temperature alkali-metal batteries hold any real promise. Stirling-cycle engines were added as another possibility for bus or truck applications.

Some other potential contenders often discussed in the popular press were ruled out on the basis of cost, weight, life, or availability of critical materials. Among these were the silver-zinc battery, which suffers from high cost, limited cycle life, and the fact that the

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Based on a paper contributed by the ASME Diesel and Gas Engine Power Division.

[2] Kirk, R., and Dawson, D., "Low Pollution Engines: Government Perspectives on Unconventional Engines for Vehicles," ASME Paper No. 69-WA/APC-5.

entire annual production of silver would provide batteries for only a small portion of the annual automobile production, and the fuel cell in its various forms, all of which are heavy, expensive, and cannot yet utilize easily available fuels.

Among the alkali-metal batteries listed as favorable, the lithium-chlorine and sodium-sulfur pairs have received the most attention. These must operate at high temperatures (1100 and 500 F respectively), and present serious difficulties with respect to safety and start-up. The authors list these as possibilities for long-term application which they define as 10 or more years from the inauguration of a serious research and development effort. Thus, only the steam engine and gas turbine are serious contenders over the next several years.

It hardly needs to be said that the use of battery-powered automobiles would not eliminate pollution due to combustion, but would rather shift it from the engine to the central power plant. The result would be a shift in the nature of the pollutants, from unburned hydrocarbons to sulfur dioxide for example, but might not effect a substantial overall improvement. If nuclear power plants are considered, then thermal and radioactive pollution are produced, with thermal pollution probably the most difficult to control. While the central station can operate at a higher efficiency than the automobile engine, the product of the long line of efficiencies from central power station through transmission lines, transformers, battery chargers, battery discharge, and motor and controls would probably be less, or at least no greater, than that of the individual engine.

Serious Contenders

Of the two serious contenders over a reasonably short time span, the steam engine and the gas turbine, the turbine has received by far the most attention.

Gas Turbine. This device, in large-power-output units, has taken over the airways, and has made inroads into the marine and stationary power plant fields. In spite of intensive work by the major automobile companies and by several other engine builders, it has not been successful in the automobile field and is just beginning to appear in heavy truck and bus applications. There appear to be several reasons why this is so:

The gas turbine, like most prime movers other than the combustion engine, is inherently a high-power-output device, while the passenger automobile requires only a modest power source—and, hopefully, its average horsepower will decrease in the future. The high output of the turbine results from its necessarily high rotative speed. An attempt to build small gas turbine plants results in small flow passages which are difficult to manufacture with the necessary precision, and which suffer from boundary-layer effects. Turbines are also inherently constant-load, constant-speed engines and do not operate well or efficiently over the extreme range of loads and speeds demanded by the automobile. Furthermore, both materials costs and manufacturing costs are substantially higher for the turbine than for the engine, and few of the people involved in these problems predict a major change in this situation.

One of the major advantages attributed to the automotive turbine by its supporters is simplicity. They speak of only one moving part. This is a fallacy when applied to passenger-car use. The regenerator, a necessary appendage of the gas turbine for automotive use, is a complicated and expensive addition. Furthermore, the main power train of the modern internal-combustion engine, while it may appear complicated, is a highly dependable and trouble-free unit which generally operates, without major repair, for the life of the vehicle.

The many problems encountered by the public with automobile repairs and maintenance are nearly all associated with the running gear, which any road vehicle must have, and with the many auxiliary motors, valves, switches, ignition system, controls, etc. which are found in greater profusion in the gas turbine plant than in the present automobile power plant. Thus, it is unrealistic to expect fewer troubles and lower maintenance costs with a gas turbine plant, simply because the basic power unit is long-lived and trouble-free.

Steam Engine. The automotive steam engine has only recently been subjected to fairly intensive research and development, and is in a relatively underdeveloped state compared with the internal-combustion engine and gas turbine. However, it too suffers from some serious handicaps which will be difficult or impossible to overcome.

Actually, steam power plants antedate internal-combustion engines, and their theory and practice are well developed and well understood. It has long been known, for example, that the efficiency of a small simple steam plant is exceedingly poor. Large modern steam power plants have efficiencies which equal or are slightly better than those of good modern diesel engines, but these good efficiencies are achieved by the use of extreme temperatures and pressures, and by the addition to the plant of auxiliary equipment and cycle complications which are only possible in very large plants. In an automotive steam engine, these complications are impossible, and high temperatures and pressures create lubrication and other problems.

It seems unlikely then that these plants could approach the modern combustion engine in economy. Supporters of steam cars have made claims of good efficiencies, but there is a dearth of test data supporting these claims, and it is difficult to see how they could be achieved.

Both the cost and weight of the steam plant are also unfavorable compared with the current engine. General Motors' experimental steam engine, for example, was 450 lb heavier and delivered one-half the horsepower of the conventional engine which it replaced.

Other problems with Rankine-cycle plants are freezing if water is used as the working substance, and temperature limitations which will result in poorer economy if other fluids now in sight are employed.

Internal-Combustion Engine. It seems clear, then, that the internal-combustion engine is superior, and is likely to remain superior, to any potential competitor in nearly every respect except exhaust pollution. Furthermore, even though the gas turbine, the steam engine, or a battery-powered system may some day be suitable for at least some classes of automotive vehicles, there is, at the present time, no replacement sufficiently well developed to become commercially feasible within the next several years.

It seems extremely unlikely, therefore, that 10 years from now more than 10 percent of new-car production will be powered by engines other than reciprocating combustion engines. This means that we will surely build at least 100 million internal-combustion engines over the next 10 years, and that we will continue to operate this number of engines for several years beyond that. Since these engines have not yet been built, it seems unmistakably clear that the kind of air we breath 10 to 15 years from now will depend more on how we build these engines than on anything else we do in the automotive pollution field. Thus, instead of abandoning support for internal-combustion research, as the government agencies are doing in the drive for nonconventional power plants, we should be making a major effort to improve the internal-combustion engine *now*, before these millions of engines are built.

Modifications

Can the internal-combustion engine, in fact, be made relatively clean? Let us look at the directions in which we might go to achieve this goal.

The first requirement is a major change in design objective. For at least the past 30 years engines have been optimized with respect to high specific power output, smooth operation, and rapid response to throttle changes. Fuel economy has been given little attention and, until recently, exhaust emissions, none. In the current attempts to produce cleaner engines, little if any compromise in performance has been allowed, although fuel economy has been permitted to deteriorate significantly. In my opinion, proposed clean-air standards can only be met if this objective is given top priority, and all other parameters compromised as may be necessary to attain the major goal. Clearly, this may make engines rougher and less responsive, and cars less fun to drive. However, breathing clean air is fun too, and, more important, is necessary if we are to stay alive in the increasingly congested cities of tomorrow.

What specific directions may we take in the pursuit of cleaner engines?

Reduce Engine Size, Power Output. Probably the simplest step is to reduce engine size and power output. A low-horsepower engine burns less fuel per mile, and, since it can be built to burn it as completely as a large engine, will produce less pollution per vehicle mile. The horsepower race has been justified for years on the basis of increased safety, i.e., extra power available to get out of a tight spot. Statistics accumulated over the years have demonstrated that the opposite is true, and insurance companies are now charging a higher premium for "muscle" cars. Since even a full-sized car uses only about 35 hp when cruising at turnpike speed, 100 hp should be adequate for all normal purposes.

Improve Carburetors and Manifolds. Beyond a reduction in engine size, several relatively minor engine modifications can be employed to reduce emissions. Improved carburetors and manifolding to reduce variations in mixture ratio from cylinder to cylinder will permit leaner overall mixtures, and hence more complete combustion. Combustion-chamber configuration changes directed toward reducing surface-volume ratios and eliminating quench regions can have a beneficial effect. These methods have been pursued by engine designers, but within limits. Rich mixtures burn better and smoother than lean ones and can be, and are, used to cover poor carburetor, manifold, and combustion-chamber designs with a resulting adverse effect on emissions. Styling also imposes constraints. Low hood profiles, for example, leave insufficient room for a really good carburetor. Thus, performance and styling continue to be given greater consideration than complete combustion.

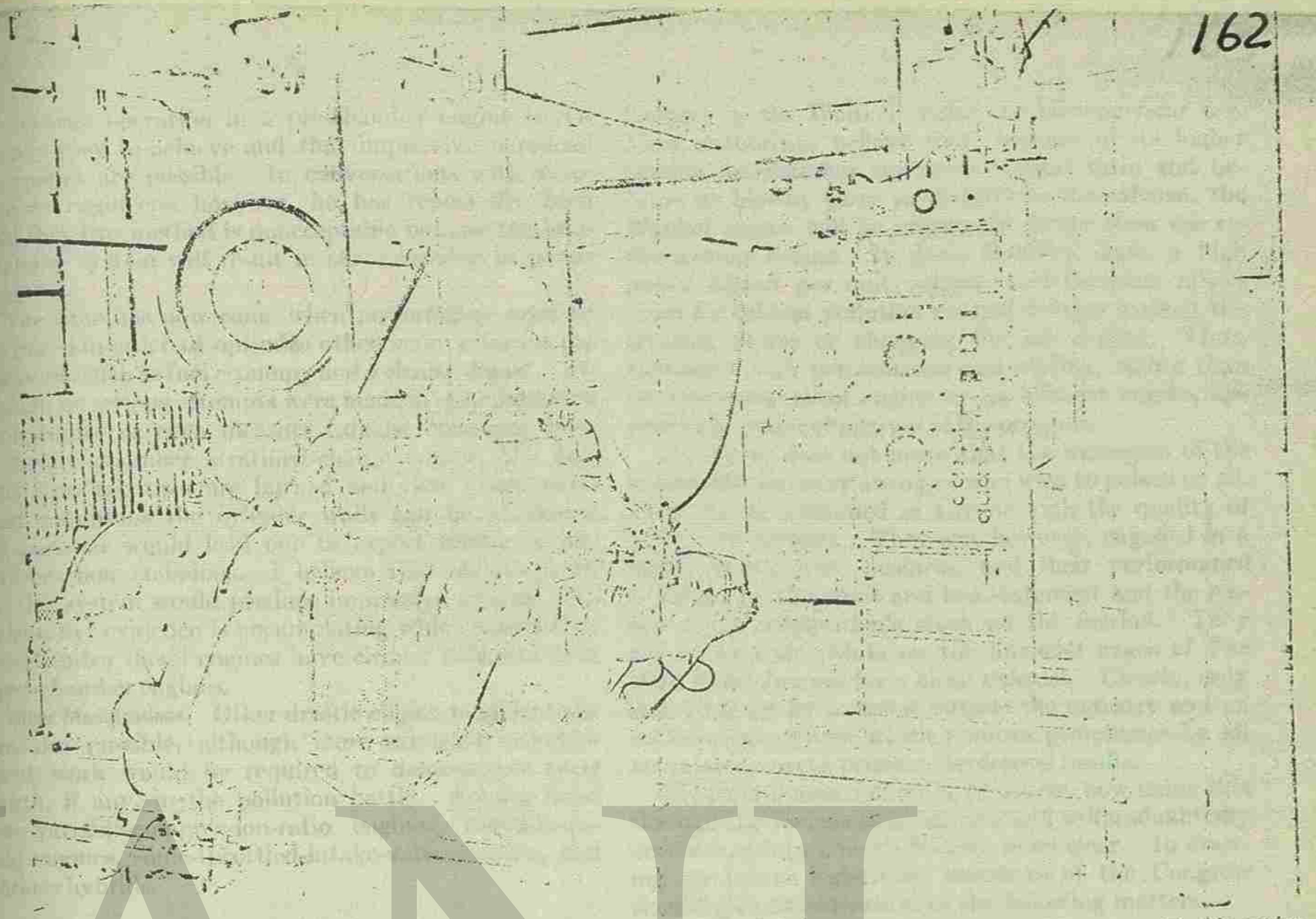
Eliminate Lead in Gasoline. Lead compounds increase the hydrocarbon content of exhaust gases both directly and as a result of lead-induced engine deposits which increase with time. Most of the solid particles in the engine exhaust are lead compounds, and if, as seems inevitable, particulates are restricted by law in the future, the elimination of lead will be almost mandatory. Probably the major advantage of lead-free fuel, however, will be to make possible long-lived exhaust catalytic converters which will essentially eliminate unburned hydrocarbons from the exhaust. The trouble-free life of exhaust-manifold reactors and exhaust-gas recirculation systems will also be extended by the use of lead-free fuel.

A great deal of misinformation has been circulated concerning the cost of lead elimination. The literature, both technical and popular, abounds with estimates of the high cost of rebuilding refineries to produce high-octane lead-free fuel and of the increased cost of this fuel to the consumer. Statements are also made to the effect that such gasoline will increase rather than decrease smog formation. All of these estimates are based on the assumption that octane numbers will remain at present levels, and, without lead, will be maintained by the addition of large amounts of aromatic compounds to the gasoline.

Actually, all that needs to be done is to reduce or remove the lead, let the octane number decrease, and lower the compression ratios of new engines to the point where the unleaded fuel will not cause detonation. Obviously, high-octane fuel will still be needed for the high-compression-ratio engines now on the road, but only a fraction of current engines have this requirement and these will gradually be replaced. Many cars now using high-octane high-lead gasoline do not require this fuel and the concomitant expense; an educational campaign emphasizing this fact would reduce substantially the use of such fuel.

Lowering engine compression ratios, of course, will somewhat decrease the efficiency and specific output of engines, but the loss will be more than compensated if total engine horsepower is reduced as suggested in the foregoing. Compression ratios have increased from approximately 6 to 10 over the past 30 years, with no improvement in miles per gallon; the increased efficiency of the engine has been cancelled by overpowering, with a resulting low load factor during all normal driving.

From the point of view of the consumer, compression ratios and octane numbers have been, for some time, beyond the economic limit. Assuming that an



View of I-C research engine used by the author in research on the stratified-charge engine. If commercially successful, this engine will run on a leaner overall air–fuel ratio and have the ability to cut off fuel flow during deceleration, a period during which combustion is extremely poor. Although engine will result in a modest loss of performance, it will be more than compensated for by greater fuel economy and a cleaner exhaust.

increase in compression ratio from 8.5 to 10 will correspond to the difference between regular and premium fuel, the theoretical increase in efficiency due to increased compression ratio is about 5 percent, while the increase in fuel cost at current prices is more than 10 percent.

Drastic Modifications

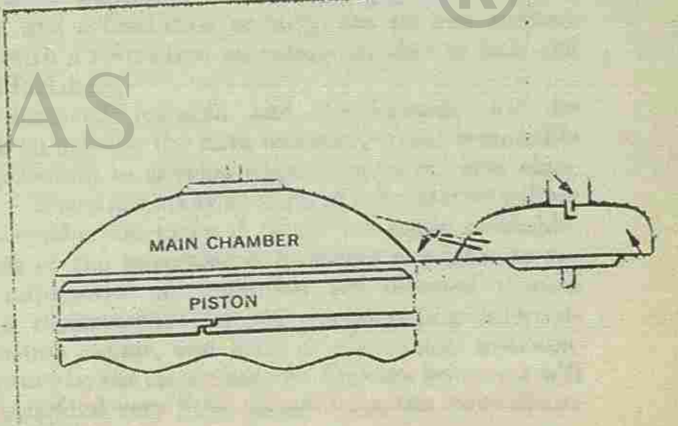
The modifications mentioned thus far have been relatively minor and have already been pursued, at least to some extent, by engine builders. If high performance were dropped as a major objective, they could be pushed much further with still greater gains in emission control. In order to produce still greater improvements, more drastic measures will need to be employed.

Fuel-Injection System. One such measure would be the substitution of a fuel-injection system for the carburetor. Fuel injection would have many beneficial effects, among which are a more uniform and hence leaner overall air–fuel ratio and the ability to cut off fuel flow completely during deceleration, a period during which combustion is particularly poor. One of the major difficulties with producing a simple fuel-injection system for the spark-ignition engine is the necessity to meter and control both air and fuel flow to maintain a combustible mixture. This problem is eliminated if another major change is employed, i.e., the use of stratified-charge operation.

Stratified-Charge Operation. Stratified-charge operation of spark-ignition engines has certain well-known advantages, chief among which are high part-load economy and the use of a throttleless intake manifold, which makes possible the simpler fuel-injection system. Although the principles of stratified-charge operation have been known for many years, serious work on the method has only recently been undertaken by engine builders, and even now only open-chamber systems have been seriously investigated. The problem of maintaining mixture ratio imbalance of the right kind and in the proper places in an open chamber under all loads and speeds is indeed difficult, and only partial success has been obtained thus far.

This author has demonstrated in the engineering laboratories at the University of Rochester that strati-

Configuration of the stratified-engine's divided combustion chamber.



fied-charge operation in a pre-chamber engine is relatively easy to achieve and that impressive part-load economies are possible. In conversations with automotive engineers, however, he has repeatedly been told that this method is unacceptable because the two-chamber system will result in some sacrifice in power output.

The time has now come when performance *must* be sacrificed in order to optimize other, more relevant parameters, such as fuel economy and a clean exhaust. Although no serious attempts were made in my laboratory to optimize or even measure exhaust emissions from a divided-chamber stratified-charge engine, the fact that lean mixtures are burned and that under part-load conditions the cylinder walls can be blanketed by pure air would lead one to expect relatively low hydrocarbon emissions. I believe that serious work on this system would produce impressive results. Incidentally, evidence is accumulating which shows that pre-chamber diesel engines have cleaner exhausts than open-chamber engines.

Other Modifications. Other drastic engine modifications are also possible, although more extensive development work would be required to demonstrate their worth, if any, in the pollution battle. Among these are variable-compression-ratio engines, tuned-manifold engines, sonic-throttled-intake-valve engines, and various hybrids.

Diesel Engine as a Substitute

The diesel engine may also be a reasonable candidate as a replacement for the spark-ignition engine in passenger vehicles. This engine has already taken over the truck and bus fields, and is finding some use in taxi and passenger-car applications. Although it has the reputation among the general public of producing smoke and obnoxious odors, the best current diesel engines are actually very good and can probably already meet the 1975 Clean Air Act standards. They suffer from higher noise levels, greater roughness, and lower specific output than current passenger-car engines, but they compensate by providing better economy and greater reliability. Again, satisfactory emission levels will cost something in power and smoothness, and the diesel engine may provide the best all-around solution.

Discussion

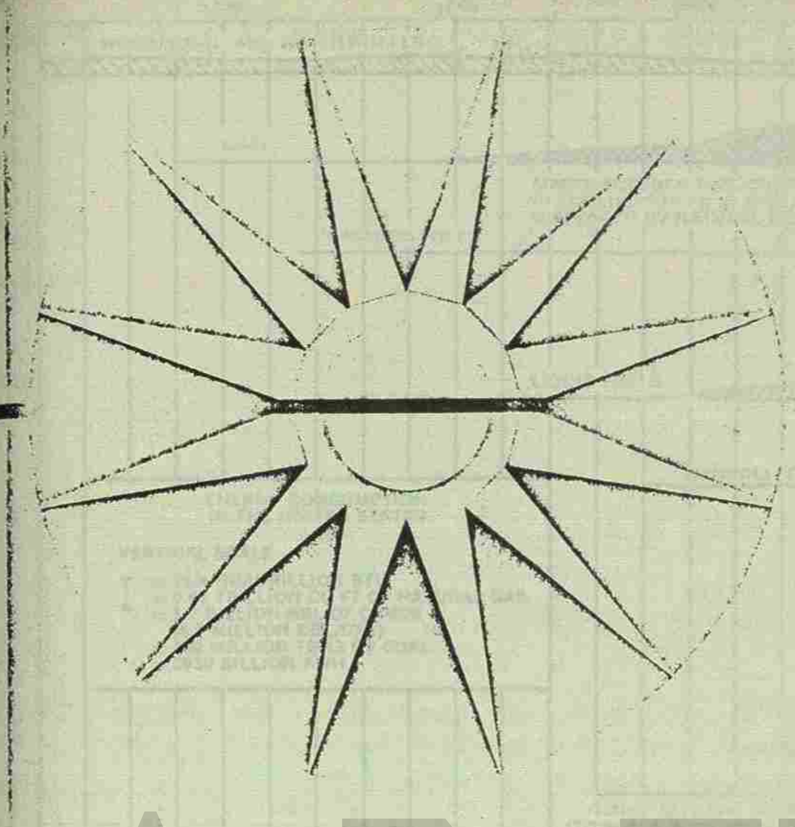
What progress have the automobile companies made to date? A good deal, actually, for current production engines produce only about one-quarter of the unburned hydrocarbons and carbon monoxide of uncontrolled engines. This improvement has been produced, however, at the cost of increased fuel consumption and increased maintenance problems in an effort to preserve performance at unnecessary levels.

The writer has always strongly believed that regulatory agencies should only set performance specifications, and should give equipment designers a free hand in their choice of how the standards are to be met. However, observations in the engine pollution field clearly show this attitude is not sound, for the engine builders are clearly working to preserve performance and let economy and reliability deteriorate. This feeling is reinforced by the recent interest of one manufacturer in the Wankel engine for passenger-car use. Most authorities believe that, because of its higher combustion-chamber surface-to-volume ratio and because its blowby gases go directly to the exhaust, the Wankel engine will be inherently dirtier than the reciprocating engine. It does, however, have a high power output per unit volume, and therefore allows room for add-on pollution control devices without decreasing power or changing the car styling. Thus, continued high performance and styling, rather than an inherently clean engine or an efficient engine, appear to be major objectives of the program.

The above does not mean that the managers of the automobile industry are ogres who wish to poison us all. They are as concerned as anyone with the quality of the air we breathe. They are, however, engaged in a highly competitive business, and their performance is judged by the profit and loss statement and the record of the corporation's stock on the market. They get no brownie points on the financial pages of *The Wall Street Journal* for a clean exhaust. Clearly, only standards set by someone outside the industry and an enforcement system which requires compliance by all manufacturers can produce the desired results.

The federal government is, of course, now doing this through the various clean air acts and will undoubtedly do more as future needs become more clear. In drawing up future legislation, members of the Congress should give consideration to the following matters:

- Emission standards must be strict enough to produce the desired result, but not more restrictive than is necessary or possible, or economically sound. Specifying, for example, an unattainable combination of unburned hydrocarbons and oxides of nitrogen would either make the law unenforceable or rule all reciprocating-engine-driven cars off the road when no replacement is available. Similarly, forcing an increased cost of several hundred dollars per vehicle to reduce pollutants to within a few percent of complete elimination may have a much lower cost-effectiveness than spending the same money (which comes ultimately from the same consumers) to reduce power plant or industrial pollutants to a lower level.
- Restrictions, in addition to exhaust pollution levels, should be imposed in order to insure that the cleaner exhaust is not obtained at the expense of fuel consumption and vehicle cost, with performance and styling immune. These restrictions might take the form of a horsepower limitation or a steeply graduated tax on power, and a limitation or steep tax on lead content along with a restriction on octane number to hold the cost of fuel down.
- Additional research and development will be needed to provide the data necessary to set reasonable standards and to develop engines to meet these standards. There are many competent laboratories willing to undertake the tasks if funds are made available. If most of the government resources available to reduce automotive air pollution are directed toward finding replacements for the reciprocating internal-combustion engine, and little or none made available to improve it, the air we breathe 10 years from now will have benefited very little indeed from the expenditure of these funds.



THE SOLAR ERA

Part 1—The Practical Promise

There has been a new source of energy every 30 to 40 years. The most recent is nuclear. By the century's end it could be solar energy to supplement both nuclear energy and the dwindling supplies of natural gas, oil, and coal. In addition to power and heat, this primal energy source—aided by chemistry and other resources—could produce fuels and lubricants for mobile equipment, rubber, plastics, and other petrochemicals.

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Had it not been for an abundance of fossil fuels—coal, oil, and natural gas—we might today have a solar-energy economy just as effective and efficient as our fossil-fuel economy. If need had forced man to devote the phenomenal ingenuity and inventiveness which he has displayed in the past 150 years to the development of devices for the utilization of solar energy instead of fossil fuels, we might, today, have huge solar-energy plants and complexes, similar to our oil-refinery and chemical complexes, where the sun's energy would be collected, concentrated, and stored to produce not only electric power, but a whole host of other things.

As it is, however, solar energy is so diffuse and intermittent when it reaches the earth that it is unlikely to be used extensively as long as fossil fuels remain abundant and readily accessible worldwide.

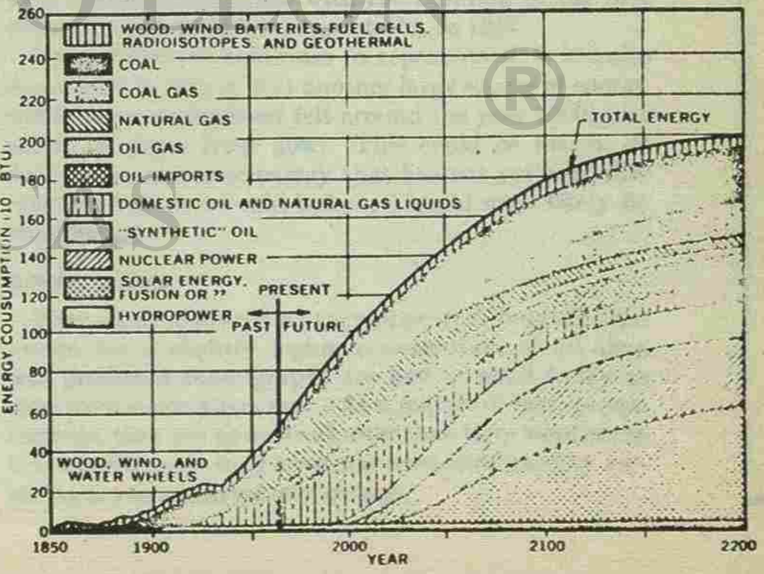
The large amount of area required to collect solar energy and the cost of the collection, storage, and conversion equipment involved prevent the *widespread* use of solar heaters, solar houses, solar cookers, solar evaporators and desalinators, solar power generators, etc., as long as fossil fuels are available to do the same job automatically, night and day, without cloud interference.

Now, though, we are beginning to become more and more aware of the fact that this bounty of fossil fuels cannot last.

Need for Solar Energy

In 1965, seven years ago, at the Solar Energy Society meeting in Phoenix, Ariz., the author presented the graph [1][1] which is shown in Fig. 1.

Fig. 1 Energy sources in the U.S.



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[1] Numbers in brackets designate References at end of article.

Based on a paper contributed by the ASME Solar Energy Applications Group.

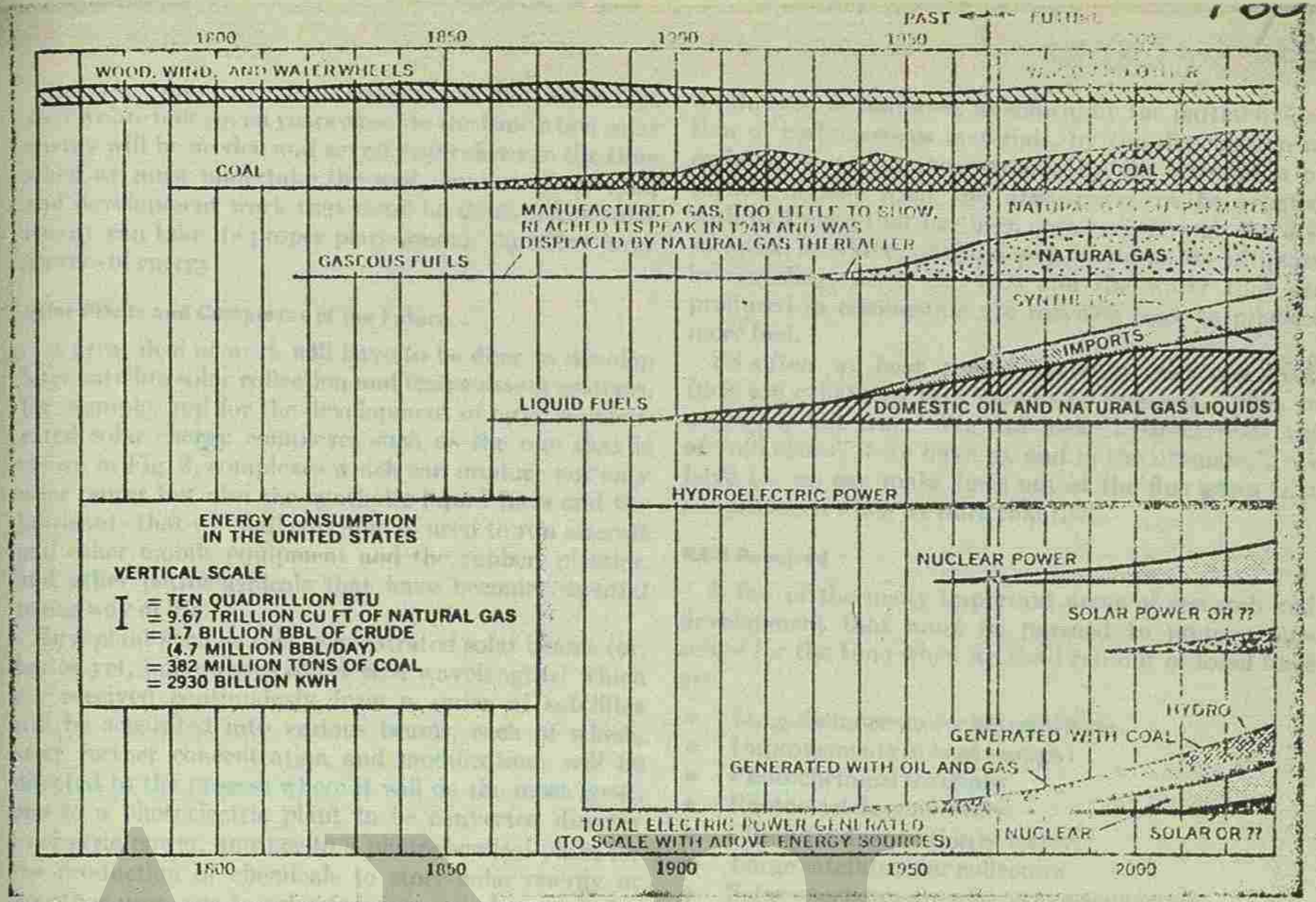


Fig. 2 Energy consumption, chronologically, in the U.S.

This graph showed that 30 to 50 years from now a new large source of energy will be needed to supplement nuclear energy and the world's dwindling supply of fossil fuels. It was suggested then that this new large source of energy might very well be solar energy.

It was also suggested then that this large amount of energy might "be collected and concentrated with satellites and then transmitted to the earth in concentrated beams of selected wavelengths to minimize diffusion and masking by the atmosphere."

It was pointed out that all the energy that was being consumed in the U. S. at the time could be collected from the sun with a single satellite only 21.5 mi in diameter.

Chronological Development

This graph has also been used in lecture tours made by the author for various institutions. For convenience, a modification of this same graph was used—one where the various segments are replotted, still to scale and in proportion with each other, but in a horizontal position as shown in Fig. 2 [2].

In Fig. 2, the various sources of energy are arranged in the order in which they were developed chronologically, and this graph shows very clearly that this country has developed a new source of energy every 30 or 40 years.

First, after wood, wind, and water wheels, it was coal. Although coal started being used in 1780 or so, it was not until 1870, after the development of several of the more modern energy-consuming machines such as steam engines, locomotives, cotton gins, lathes, etc., that coal became important.

Gas came next, in 1816, but this too did not become important until many years later when in 1930 natural gas began being piped long distances to market.

Oil was discovered in 1859, but it did not become an important item of commerce until 1919 when the self-starter was invented and the mass production of internal-combustion engines began.

The next new source of energy was hydroelectric power in 1890. This had to await the invention and development of electric power generators which became commercial with the building of the first steam-electric power plant in New York City in 1883. The bottom segment in Fig. 2 shows how the total electric power generation has grown since then.

Following the development of hydroelectric power generation, over half a century elapsed before another new source of energy was discovered—nuclear fission. This became commercial with the building of the first prototype plant in Shippingport, Pa., in 1957.

Now, if history continues to repeat itself, it is quite reasonable to expect that another large source of energy will begin to make itself felt around the year 2000, just about 30 years from now. This could be fusion, or some other source of energy that has not yet been discovered, but, as we said before, it could most likely be solar energy.

Still Up to Date

New data, analyzed as they appeared, indicate that except for a slightly higher consumption of oil than was predicted these graphs are just as good today as they were seven years ago. As a matter of fact, as predictions, they are now even better than they were seven years ago because they have now been reinforced by surviving seven whole years of change.

The only difference between now and then is the fact that we are now seven years closer to the time when solar energy will be needed and seven years closer to the time when we must undertake the vast amount of research and development work that must be done before solar energy can take its proper place among the other large sources of energy.

Solar Plants and Complexes of the Future

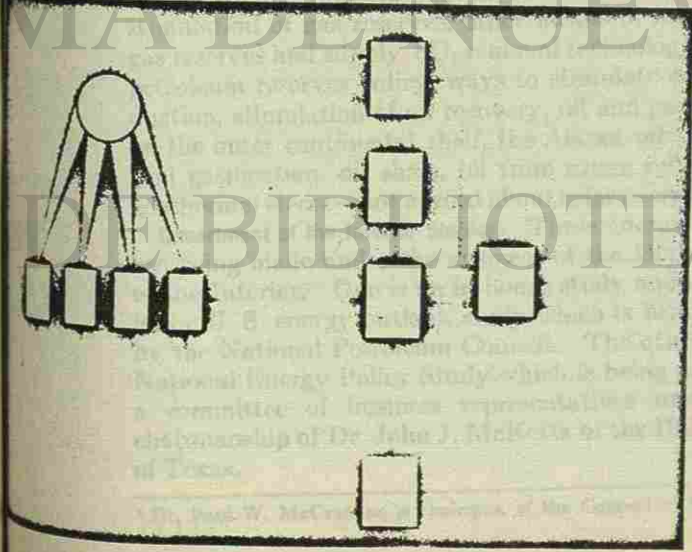
A great deal of work will have to be done to develop large satellite solar collection and transmission systems, for example, and for the development of large sophisticated solar energy complexes such as the one that is shown in Fig. 3, complexes which can produce not only solar power but also the synthetic liquid fuels and the lubricants that we shall continue to need to run aircraft and other mobile equipment and the rubber, plastics, and other petrochemicals that have become essential to our way of life.

In a plant such as this, concentrated solar beams (or, better yet, microwaves of selected wavelengths) which are received continuously from a series of satellites will be separated into various beams, each of which, after further concentration and modification, will be directed to the process where it will do the most good: one to a photoelectric plant to be converted directly to electric power, another to a photochemical plant for the production of chemicals to store solar energy or for other uses, one to solar furnaces or solar ponds for the production of heat for processing purposes, and others for more specific purposes such as the dissociation of water (with the aid of a catalyst not yet discovered) to produce hydrogen and oxygen which can be used as fuel for fuel cells in homes or as raw materials for the manufacture of fertilizers, synthetic hydrocarbons, and chemicals such as rubber, plastics, fibers, solvents, etc., as shown in Fig. 3.

Hydrogenation of Carbon Monoxide

In a complex such as this, the hydrogenation of carbon monoxide—a process that is already well known—can be used to produce hydrocarbons and chemicals similar to those that we use today. The hydrogen and carbon monoxide that are required to do this can be obtained, as shown, by the partial oxidation of carbonaceous materials, by the dissociation of carbonates, or, in the extreme, by the extraction of carbon dioxide from the atmosphere to be reacted with hydrogen that has been obtained through the dissociation of water. Such a step would be the ultimate in recycling, when the CO_2 and the water that are produced in combustion are recycled back to produce more fuel.

Fig. 3 Solar energy complex.



So often we hear people say that once our fossil fuels are exhausted they cannot be replaced. This, of course, is not true. We can make hydrocarbons out of "old shoes" if we have to, and in the ultimate, if we have to, we can make fuels out of the flue gases that are produced when we burn that fuel.

R&D Required

A few of the many important areas of research and development that must be pursued to prepare ourselves for the time when we shall run out of fossil fuels are:

- Long-distance power transmission
- Improvements in heat pumps
- Photochemical reactions
- Photoelectric convertors
- Catalytic dissociation of water
- Large satellite solar collectors
- Solar-spectrum–to–microwave convertors.

Because solar complexes such as that shown in Fig. 3 will have to be located in large uninhabited areas of the world, deserts and the like, we must learn how to transmit electrical energy over long distances more effectively, perhaps without wires.

We should also effect improvements in heat pumps so that these can be used to supplement the sun for the heating and air conditioning of homes and other buildings. Also, we most assuredly must do a lot more work on the study of photochemical reactions in which may lie the solution to the problem of storing solar energy.

We should, of course, continue the improvement of solar cells and of thermoelectric and thermionic devices for the direct conversion of solar energy to electricity. Also, we must improve the methods and the cost of producing, storing, and transporting hydrogen and oxygen so that these can be used in fuel cells in homes and also in the manufacture of chemicals and synthetic liquid fuels as we described before.

In addition, a great deal of work needs to be done on the development of large satellite solar collection and transmission systems. This idea was first suggested by the author in 1965 [1], and it has since been expanded upon and shown to be feasible, even with present technology, by Glaser [3-7]. The satellite solar collectors may be composed of solar cells which can be coupled directly to d-c–to–microwave convertors, as Glaser has suggested, or the collectors may be simple mirror-like parabaloid devices focused on laser-like convertors or on a conversion system consisting of a dynamic Rankine-type generator coupled to Klystron-type convertors.

Other things that are required are materials that are selective absorbers of solar quanta, cheap lens-like solar concentrators, and cheap automatic movements so that solar collectors can be made to follow the sun, all to make solar-collector working temperatures high enough to generate steam under pressure for conventional turbogenerators.

In addition, we need to develop photochemical reactions which can be used to produce compounds to store solar energy, compounds which can be burned or dissociated when needed. Such compounds might also be used to handle and transport hydrogen and oxygen in solid or liquid forms more conveniently.

A great deal of work has been done on the use of the sun and acreage to produce, through photosynthesis, wood and other vegetation which can be used as fuel directly or as a source of alcohols (liquid fuel). More combustible material can probably be made with the same acreage, if a photochemical reaction more rapid and more efficient than photosynthesis is used. Selected chemicals in solution exposed to the sun in solar ponds to form solid precipitates are envisaged.

Government Support Crucial

Work directed toward systems such as these will be extremely expensive and obviously cannot be expected to be supported through profit motivation alone. It simply must be supported by the governments of the world, just as atomic energy was, as a result of long-range visionary planning.

The problem before us today, therefore, is to promote awareness of the ultimate need for solar energy and to enlist the assistance of those who are in a position to allocate funds and facilities for the support of the large amount of research that must be done to prepare for this solar era.

Energy Studies in Progress

Because the U. S. government has already become very seriously concerned about the energy picture of the immediate future, as a result of certain local shortages of coal and natural gas, power brownouts, nuclear-power-plant delays, etc., there are several energy studies that are now underway or proposed by various agencies of the government. These are:

McCracken Fuels Committee. The McCracken[2] Committee study, which is being made for the executive office of the president, will report on a large number of specific items: nuclear fast-breeder reactors, nuclear stimulation of gas reserves, other means of improving gas reserves and supply, SO_2 removal technology, naval petroleum reserves policy, ways to stimulate coal production, stimulation of oil recovery, oil and gas leasing on the outer continental shelf, the Alaska oil pipeline, coal gasification, oil shale, oil from urban refuse, and geothermal steam—not a word about solar energy.

Department of the Interior Studies. Three energy studies are being made under the auspices of the Department of the Interior. One is an in-house study and another is the U. S. energy outlook study which is being made by the National Petroleum Council. The other is the National Energy Policy Study which is being made by a committee of business representatives under the chairmanship of Dr. John J. McKetta of the University of Texas.

Bills in Congress. In addition to these studies already in progress, the Senate has favorably reported out of committee a resolution, Resolution 45, which empowers the Committee on Interior and Insular Affairs, in cooperation with several other agencies of the government, to make a *major* energy study to be completed in 18 months. This resolution, sponsored by Senators Randolph (D–W. Va.) and Jackson (D–Wash.), is a substitute for the National Fuels and Energy Commission policy review which failed to pass in the last Congress.

The proponents of Resolution 45 have urged that a highly qualified staff be obtained to make this study, and Senator Jackson has suggested that it be directed by S. David Freeman, who was the director of the energy policy staff in the president's Office of Science and Technology. This office is continuously studying energy supply and policy matters and has contributed materially to the McCracken Committee work.

House bill HR-258 and others similar to it propose the establishment of a commission on fuels and energy. This is a reintroduction of the proposal that was covered by S.4092 which died in committee last year. There has been no action yet on this measure.

Another study of interest is that which is being made for the National Science Foundation on the "Growth and Demand for Energy" by the Rand Corp. The National Science Foundation is also sponsoring a study on "Environment and Technology Assessment" by the Oak Ridge National Laboratory.

Through participation in studies of this kind and through participation in congressional hearings on the subject, we should take advantage of every opportunity to see that solar energy is not overlooked.

Another timely opportunity to promote research and development work in the field presents itself as a result of the cutbacks that are now occurring in defense, aerospace, and nuclear-energy research. These cutbacks are releasing not only a large number of scientists and engineers, but also a large number of research facilities that are already admirably suited to do some of the sophisticated work that is required in the solar energy field.

So far, except for the support of the work that has been done on solar cells, thermionics, and thermoelectric devices for the space and defense agencies, the amount of money that has been allocated to solar research has been negligible.

What is needed, of course, is an "Office of Solar Energy Research" like the Office of Coal Research, or better yet, a "Solar Energy Commission" like the Atomic Energy Commission.

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[2] Dr. Paul W. McCracken is chairman of the Council of Economic Advisers.

trends in energy needs

Energy requirements and availability of energy supplies are subjects of increasing interest. Here is a briefing on U. S. energy requirements as related to total world requirements, on the sources of energy consumed in the U. S., the end uses of energy consumed in the U. S., and predictions as to the rate of increase in U. S. energy consumption.

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In 1958, with a world population of about 2.9 billion people, the total energy consumption of the human race was equivalent to consuming about 3700 million metric tons of coal. That energy was provided 54 percent by solid fuels, primarily coal; 30 percent by liquid fuels, primarily oil; 14 percent by gas fuels, primarily natural gas; and 2 percent by hydro and nuclear sources combined, but essentially hydro.

In 1968, with a world population of about 3.5 billion people, the total energy consumption was equal to consuming about 6000 million metric tons of coal. Three facts are of interest:

1 During the 10-year period 1958–1968 the world population increased by about 21 percent. However, the total world energy consumption increased by 62 percent. This means that energy consumption per capita increased nearly 35 percent in just 10 years.

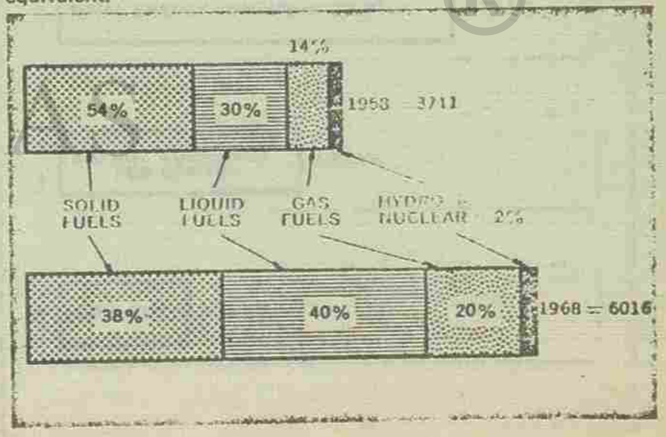
2 During that 10-year period, there have been significant changes in the sources of energy used. The net effect of this changing pattern of energy use is shown in Fig. 1. Solid fuels decreased from 54 to 38 percent of total energy consumption, liquid fuels increased from 30 to 40 percent, and gaseous fuels from 14 to 20 percent. Hydro and nuclear combined remained in the range of 2 to 3 percent.

3. The use of all raw-energy sources increased in absolute quantities. For solid fuels, 38 percent of 6016 million tons in 1968 represents 15 percent greater tonnage than 54 percent of 3711 million metric tons in 1958. Similarly, the consumption of liquid fuels increased by 118 percent, gaseous fuels by 130 percent, and hydro and nuclear combined by 80 percent.

Worldwide, the decreasing dependence on solid fuels and the increasing dependence on liquid and gaseous fuels indicates the preference for the fuels most convenient to transport and use. This same pattern is evident in the U.S.

It is also evident that the human race has a tremendous need for energy in all forms and that improvements in world economies and in standards of living are related to energy consumption. Further, the bulk of our energy need is today met by tapping our nonrenewable resources of coal, oil, and gas. While we have tremendous worldwide reserves of these fuels, our reserves are not infinite.

Fig. 1 World energy consumption, millions of metric tons coal equivalent.



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[1] Vice-President. Mem. ASME.
Based on a paper contributed by the ASME Energetics Division.

TABLE 1 World Energy Consumption,

Area	Per Capita Consumption (Kg Coal Equivalent)	Percent of World Energy Consumption	Percent of World Population
United States	10,331	34	6
Western Europe	3,312	19	10
U.S.S.R.	4,058	16	7
Japan	2,515	4	3
World Average	1,727	—	—
South America	653	2	4
Far East ex. Japan	182	3	28
Africa	294	2	10

Source: U.N. Statistical Papers

Average World Energy Consumption

While the 1968 average world energy consumption was the equivalent of consuming 1727 kg of coal per capita, there are tremendous differences in total energy consumption, even among the countries we consider highly industrialized and developed. Table 1 illustrates the differences for a few areas and indicates that the U. S. has the largest per capita energy appetite.

The per capita energy consumption in the U. S. is about six times the world average, three times the average for Western Europe, and from 35 to 55 times the average for the less developed areas of Africa and the Far East, excluding Japan.

The U. S., with about 6 percent of world population, consumes 34 percent of world energy. The U. S., together with Western Europe and the U.S.S.R., with a combined population less than 25 percent of world total, account for about 70 percent of world energy consumption.

It is evident from these data that industrialization, economic well-being, and general standard of living are directly related to energy use per capita. Just imagine the tremendous increase in world energy requirements if standards of living in the undeveloped countries could be raised. This is a significant political, economic, and engineering challenge.

U. S. Energy Consumption

Fig. 1 indicates that during the 10-year period 1958–1968 world energy consumption increased by 62 percent. During this period, total annual energy consumption in the U. S. increased by 50.5 percent, Fig. 2.

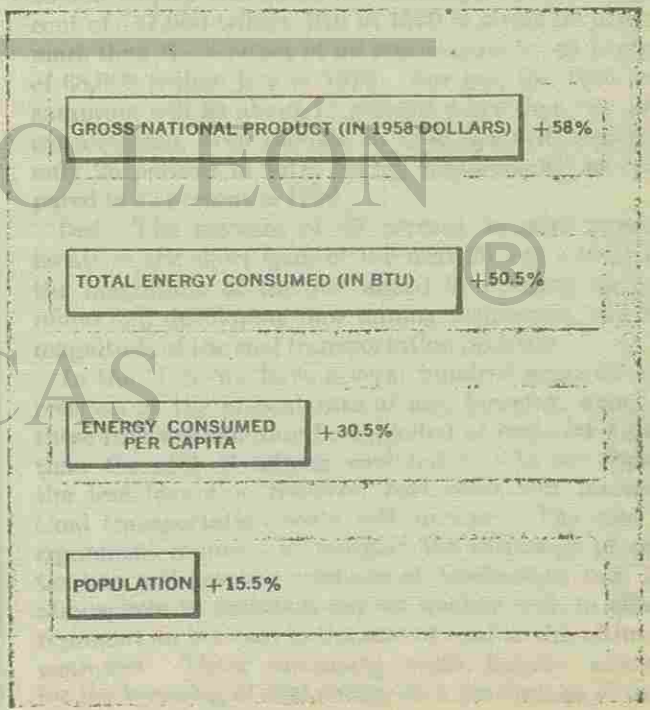
At the same time, our GNP, expressed in constant 1958 dollars, increased about 58 percent. Our population increased only 15.5 percent, resulting in an increase in energy consumption per capita of 30.5 percent.

Our population is currently increasing at the rate of about 1.3 percent per year, our total energy consumption is increasing at the rate of about 4.2 percent per year, and energy consumption per capita is increasing at about 2.7 percent per year.

The conclusion: Energy consumption is closely related to the total value of all goods and services produced in the U. S.; it is related to and is a vital ingredient of our economic growth, our per capita income, and the enhancement of our standard of living.

The fact that energy is a fundamental necessity of our economy only becomes apparent to the average citizen when he is deprived of its benefits, such as during an electric power failure, or shortage of gas or oil for heating purposes, or shortage of gasoline for his automobile. Temporary interruptions to energy supplies have been so infrequent in the past and of such short duration that few people realize that our economy is really dependent on an abundant supply of raw-energy resources at reasonable cost.

Fig. 2 U.S. energy consumption, percent change, 1968 vs. 1958.



During 1960, the U. S. consumed about 45,000 trillion Btu, Fig. 3. During the decade of the 1960s energy consumption increased by about 50 percent, so that in 1970 total U. S. consumption of energy increased to 68,000 trillion Btu annually. We expect that total energy consumption will continue to increase during the 1970s at about the same rate as in the second half of the 1960s, assuming no serious economic recession, so that by 1980 our total annual consumption will be at the rate of 104,000 trillion Btu, or about 53 percent greater than in 1970.

It seems reasonable that some day our rate of increase in energy consumption, in economic growth, and in value of goods and services produced will begin to slow down. Some day, we should begin to approach saturation in the improvement of our standard of living. No one has a crystal ball, however, that can predict when, or even if, this will occur. But during the decade of the 1980s our rate of annual increase in energy consumption is expected to slacken. Total U. S. energy consumption in 1990 will be 147,000 trillion Btu, or about 40 percent greater than in 1980, but even so our 1990 energy needs will be more than double the needs actually recorded for 1970.

Many things might occur that could drastically alter these predictions of future total energy consumption, both in the U. S. and worldwide. All energy consumption affects our environment. In the past, our environment had a greater capacity to maintain itself than we had to influence its natural balance by our industrial and consumer-oriented activities. The by-products of energy consumption include the discharge of the products of combustion into our atmosphere and the discharge of heat into the atmosphere and into our water resources. With our increasing population and our increasing energy consumption for comfort, industrial uses, transportation, electric power generation, and other purposes, we must now manage and conserve our environmental resources. This is the thrust of environmental legislation.

Our predictions for 1980 and 1990 assume that methods and practices will be developed and adopted to manage our environment without curbing the increase in total energy consumption. These predictions also assume that through intensified exploration the natural resources will be found, developed, exploited, and transported to support the total energy needs of the country.

Fig. 3 Actual U.S. energy consumption for 1960 and 1970 plus predictions for 1980 and 1990.

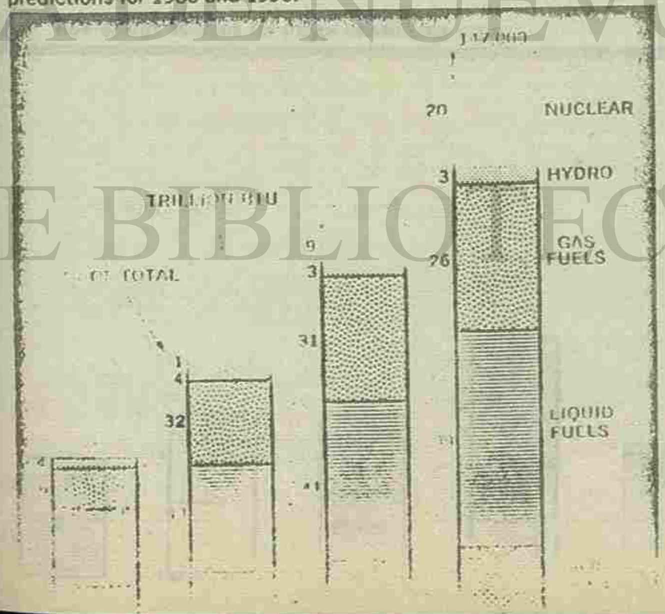


Fig. 3 also illustrates the major sources of energy and the changing consumer preferences for energy sources.

Nuclear sources provided an insignificant amount of the total energy needs in 1960 (so small it is not even shown on the bar) and only about 1 percent in 1970. We predict a rapid increase in the use of nuclear energy, primarily for electric power generation, and expect that nuclear will provide about 9 percent of total U. S. energy consumed in 1980 and 20 percent in 1990. It is largely the increase in nuclear that accounts for the decreasing percentages of energy to be provided by gas, oil, and coal during the next two decades and beyond.

Energy Resources

This pattern of changing use of our raw-energy resources has been and will continue to be caused partly by consumer preference and partly by economics, which in turn is affected by availability and cost of the marketable reserves. The consumer has indicated a definite preference for the more convenient energy sources, i.e., gas and oil as compared to coal. As our indigenous resources of fossil fuels are consumed, we can expect the prices of those fuels to increase due to the normal relationships of supply and demand. This will increasingly make nuclear energy an economic raw-energy source, primarily for electric power generation.

Do not be misled, however, by these declining percentages of energy consumption shown on this chart. The actual consumption of all fossil fuels will increase each year. Measured in tons of coal, 13 percent of 147,000 trillion Btu in 1990 is about 40 percent more coal than the tonnage represented by 20 percent of 68,000 trillion Btu in 1970. For liquid fuels, 38 percent of 147,000 trillion Btu in 1990 is about 90 percent more than the amount of oil represented by 43 percent of 68,000 trillion Btu in 1970. For gas, the 1990 consumption will be about 75 percent more than the 1970 consumption, even though, in 1990, gas will represent only 26 percent of total energy requirements as compared to 32 percent in 1970.

Coal. The increase of 40 percent in coal requirements in the short span of the next 20 years indicates the magnitude of the job ahead in opening up new mines and developing new mining techniques, and the magnitude of the coal transportation problem.

In the U. S. we have several hundred years of coal reserves at the present rate of use; however, many of these reserves can only be exploited at costs far higher than the cost of mining coal today. As we exploit the less favorable reserves, coal costs will increase. Coal transportation costs will increase. The cost of equipment required to mitigate the discharge of particulate and gaseous products of combustion into the atmosphere to maintain our air quality will, in effect, represent an increase in the cost of coal to the ultimate consumer. These increasing costs largely account for the lessening of coal energy as a percentage of total

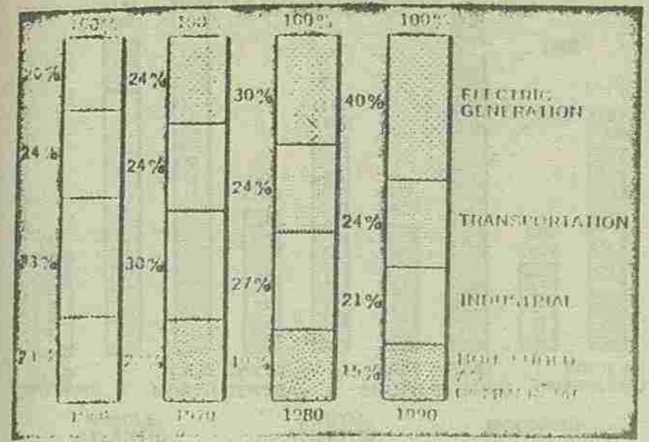


Fig. 4 Major user sectors of U.S. raw-energy consumption.

energy and the reduced rate of increase in coal tonnage requirements in the future.

Oil. Our proven U. S. oil reserves of about 39 billion barrels are only equal to about 11.8 years' supply at the 1970 consumption rate (as against 12 times in 1960). There are "probable" additional reserves (excluding Alaska) equal to perhaps 100 years' supply at the 1970 consumption rate. About 25 percent of our oil needs are imported. The huge reserves reported available in Alaska are only equal to about three years' supply at the 1970 rate of consumption. This example alone indicates the rate at which new oil reserves must be discovered and proven through an accelerated exploration program.

Gas. Our U.S. proven gas reserves of about 291 trillion cu ft are only equal to about 13.3 years' supply at the 1970 rate of consumption (as against 20 times in 1960), and there are probable additional reserves equal to 21 or more times the 1970 consumption.

In recent years, the annual rate of new discoveries of oil and gas has been less than our annual rate of consumption, resulting in decreasing reserves-to-production ratios.

An increase of 90 percent in annual oil consumption and 75 percent in annual gas consumption during the next 20 years certainly indicates the magnitude of the exploration program required both in the U. S. and worldwide to locate new reserves and develop new wells and transportation techniques.

The values on this chart indicate a cumulative 1970 to 1990 requirement of 12,600 million tons of coal plus 152 billion bbl of oil plus 600 trillion cu ft of natural gas.

Nuclear Fuel. The tremendous increase in nuclear energy indicates the need for an accelerated exploration program to locate economically obtainable reserves of uranium and other fissionable materials. Our presently known U. S. reserves of uranium are estimated to be adequate only through about 1981; however, the need for nuclear fuel will create an extensive exploration program. The reserves of fissionable nuclear fuel required will be significantly affected when the breeder reactor becomes a commercial reality, probably by the mid-1980s.

The history of the past indicates, for all fuels, that the amount of proven reserves is a direct function of the amount of exploration.

Although the problems of future supply are tremendous, these projections of future energy consumption assume that the required reserves will be available either by U. S. production or by imports from other worldwide sources.

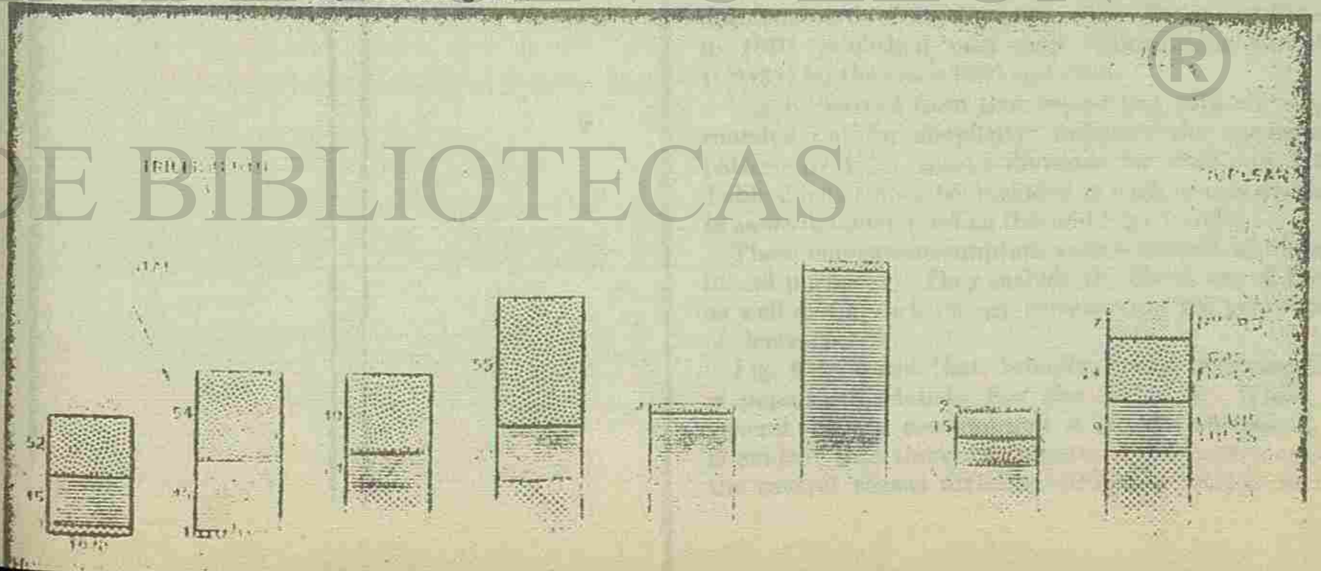
U. S. Raw-Energy Consumption and Sources

How do we use the energy we consume? Fig. 4 shows the breakdown into major use categories (household and commercial, industrial, transportation, and electric generation) as a percentage of the total energy consumption each year. Here 100 percent equals 45,000 trillion Btu in 1960, increasing to 147,000 trillion in 1990 as shown in Fig. 3.

Fig. 5 illustrates the percentage of raw energy provided by the several types of fuel resources for each of these major use categories. Only 1970 and 1990 are shown to avoid making the charts too complicated and to illustrate a reasonably long-term trend of 20 years. Coal, oil, and gas are the principal raw-energy sources for direct use in the household, commercial, and industrial markets. Today coal is an insignificant contributor to household and commercial energy use. This market is served primarily by gas and oil because of consumer preference for the convenience of these fuels. We expect this situation will continue into the future.

For industrial use, coal is a significant energy source, but provides only about 28 percent of industrial raw-

Fig. 5 Raw-energy sources for major consuming uses.



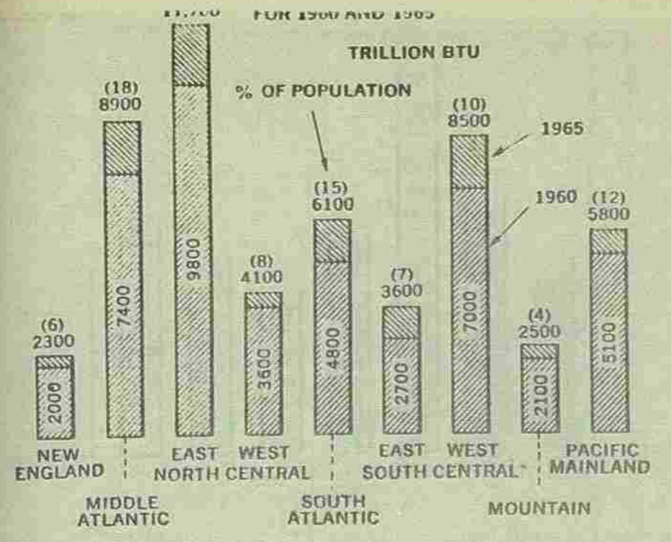


Fig. 6 Total energy consumption by U.S. census divisions.

energy needs today and will decrease to about 22 percent of industrial needs by 1990. About 75 percent of industrial raw-energy needs are furnished by petroleum products, gas and oil, and we expect that this pattern will continue into the future.

These values represent only the gas, oil, and coal consumed directly by the household, commercial, and industrial markets.

Fig. 5 also shows that practically all raw-energy requirements for transportation are provided by oil products, with a very minor percentage furnished by natural gas. We expect this situation to continue into the foreseeable future, because there is no indication today that the internal-combustion engine will not remain the primary source of motive power.

Consumption of fuel energy for the production of electric power is, however, both interesting and dramatic. Today, 46 percent of electric power is produced by coal, 12 percent by oil, 25 percent by natural gas, 15 percent by hydro, and only 2 percent or less by nuclear energy. By 1990, however, nuclear sources will account for 49 percent of electric energy produced, hydro will account for only about 7 percent, and the consumption of gas, oil, and coal for electric power generation by coal will decrease dramatically. The percentage generation by coal will decrease from 46 to 21 percent, oil from 12 to 9 percent, and gas from 25 to 14 percent.

These changing patterns, the increasing reliance on nuclear and the decreasing reliance on fossil fuels and water power, are based simply on economics. The electric power industry has no preference for any type of fuel. It will use whatever raw-energy source is the most economic to produce electric power and energy at the lowest possible cost.

As the availability of fossil fuels decreases and the cost of fossil fuels increases, it will become more and more economic to use nuclear energy for electric power generation.

Water power will become a less important source of electric power, simply because our more advantageous hydro sites have already been utilized.

Even though the percentage participation of these fuels in electric power generation will decrease, it is evident that the absolute quantities of coal, oil, and gas required for electric generation will increase substantially. For example, consider coal: 21 percent of 60,000 trillion Btu in 1990 is 70 percent more coal than is represented by 46 percent of 16,000 trillion Btu in 1970. The same type of comparison for oil and gas indicates that during the next 20 years the annual consumption of oil for electric power generation will increase by 180 percent, and gas by 110 percent.

It is clear that we are on the threshold of the nuclear era. In the next 20 years, nuclear energy will increase from less than 2 percent to about 49 percent of energy needs for electric power production, while at the same time customer preference will increase electric energy from 24 to 40 percent of the total energy consumed in the U. S. annually. The net effect is that during the next 20 years, nuclear energy will increase from less than 1 percent to about 20 percent of total U. S. raw-energy needs.

Energy-Use Patterns

Until recently, few data had been published to show how much of our total annual energy was consumed in different parts of the country. The Bureau of Mines, in 1970, published such data (Information Circular IC8434) for the years 1960 and 1965.

Fig. 6, derived from that report but with all values rounded out for simplicity, indicates the energy-use pattern by U. S. census divisions for 1960 and 1965. Table 2 lists the states included in each census division to assist in understanding this and Figs. 7 and 8.

These energy-consumption values include all energy for all purposes. They include the direct use of fuels, as well as the fuels energy consumed in the generation of electric power.

Fig. 6 indicates that, broadly, energy consumption is population-related. See also Table 3. While, in general, energy consumption is population-related, it is evident that there are important differences among the several census divisions, probably related to the

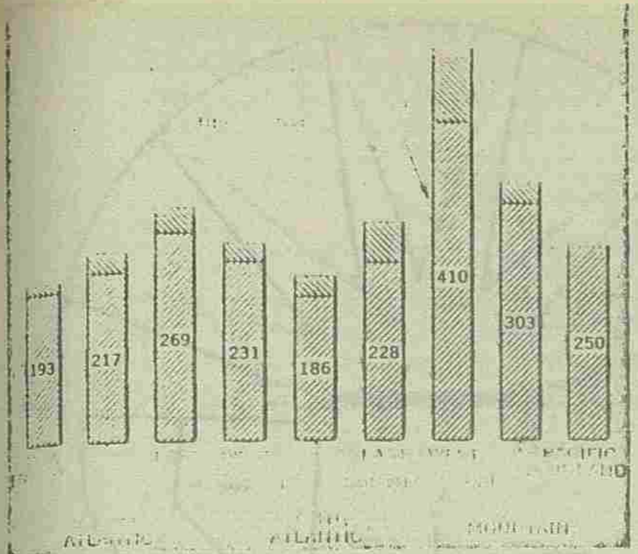


Fig. 7 Per capita energy consumption by U.S. census divisions.

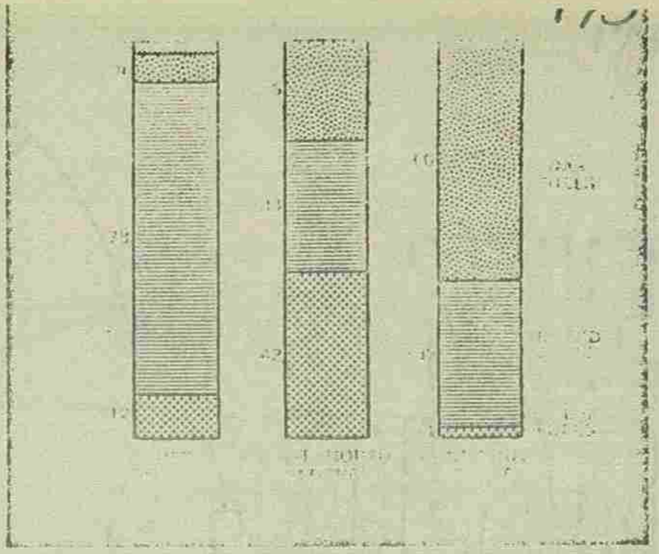


Fig. 8 Total energy consumption for selected census divisions, 1965, percentage by sources.

differences in the nature of the economic activity, although a clear pattern is not evident from these statistics.

Fig. 6 also indicates the increase in energy consumption in each census division between 1960 and 1965. The total energy consumption in each division and the rate of increase in energy demand in each division give a clear indication of where energy resources must be delivered for use, and consequently the expansion required in facilities for transportation of fuels from areas of origin to areas of use, in facilities for storage and distribution of fuels, and in the energy companies' marketing efforts.

For example, between 1960 and 1965, energy consumption in the New England division increased from 2000 to 2300 trillion Btu, or only 15 percent. The increase was 15 percent or less in the West North Central and Pacific Mainland divisions. In all other divisions, the increase was about 20 percent or more, ranging up to 27 percent in the South Atlantic and 33 percent in the East South Central divisions.

Per Capita Consumption. Fig. 7 illustrates the per capita consumption of energy in 1960 and 1965. The lowest per capita energy consumption is in the New England division and in the South Atlantic division, comprising the states of Florida, Georgia, North and South Carolina, Virginia and West Virginia, Maryland, and Delaware. These areas have no significant indigenous resources of gas or oil, and except for West Virginia have no significant reserves of coal.

The highest per capita consumption is in the West South Central division, comprising Arkansas, Louisiana, Oklahoma, and Texas, the area having the bulk of our U. S. reserves of gas and oil, probably about 75 percent or more.

Significantly, the energy consumption per capita in the areas having substantial reserves of gas and oil is more than twice that of areas deficient in fuel reserves.

Table 4 is a summary of the 1965 sources of energy consumed in each census division in terms of percentage of the total consumption for that division.

Summary

From these data and predictions it seems evident that:

1 Total energy consumption is related to population growth, and in the U. S. is increasing at a rate of about three times that of population.

2 Consumption of energy, in all forms, is a vital ingredient in our economic growth, in the continuing improvement in our standard of living, and in increasing income per capita.

3 Consumption of energy presents environmental problems, but means will be found to control the environmental impact without having to reduce our appetite for energy.

4 The energy sources that will be used and the form in which energy is used are related to technological developments, the availability of fuel resources, and consumer preferences. It is expected that all of these factors will result in electric power becoming an ever larger source of energy to the ultimate consumer in the decades ahead.

TABLE 3 1965 Population and Energy-Consumption Percentages for U.S. Census Divisions

Division	Population, Percent	Energy, Percent
New England	6	4
Middle Atlantic	18	16
East North Central	20	22
West North Central	8	8
South Atlantic	15	11
East South Central	7	7
West South Central	10	16
Mountain	4	5

TABLE 4 Percentages of Census-Division Total Consumption of Energy Sources

	1965 Percentage			
	Coal	Oil	Gas	Water Power
New England	12	78	8	2
Middle Atlantic	30	51	16	3
East North Central	42	33	25	—
West North Central	16	43	38	3
South Atlantic	32	50	16	2
East South Atlantic	39	31	25	5
West South Central	1	39	60	—
Mountain	14	37	39	10

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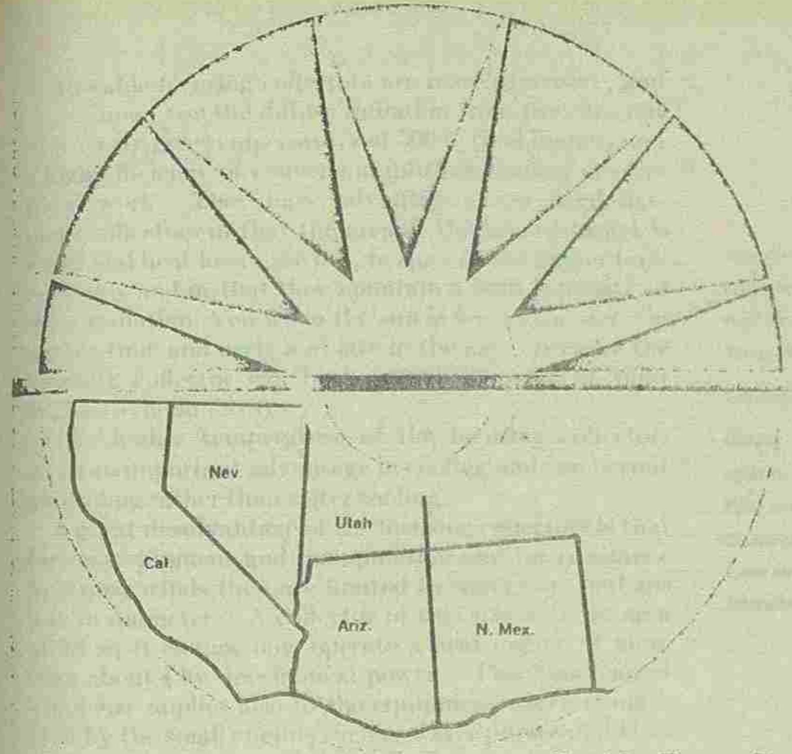

THE SOLAR ERA

Part 2—Power Production with Small Solar Engines

Theoretically, sunlight can supply all the electric power we need. Over 100 million acres of unoccupied public lands in five of our southwestern states are bathed in solar radiation sufficient to produce (using conservative conversion factors) 6.7×10^{13} kwh annually. This is 40 times the present total annual production. Small solar engines and generators can now be built for about \$1000/kw compared with \$200/kw in large conventional installations—an appreciable difference. But the cost is low enough and the rewards of success great enough to justify further research and exploration.

FARRINGTON DANIELS[1]

Solar Energy Laboratory, University of Wisconsin, Madison, Wisc.

THERE have been many technically successful, but economically unsuccessful, attempts to obtain useful power from heat engines operated by the sun. They include the use of both flat-plate and focusing collectors and operating fluids such as steam, hot air, and organic and inorganic vapors.

Silicon photovoltaic cells are the simplest converters of sunlight into electric power. They have been effective in the exploration of outer space, but they are expensive, costing now about \$50,000/kw. Cadmium sulfide photovoltaic cells are cheaper, but they are less efficient than the silicon cells, and they still cost several thousand dollars per kilowatt. The cost of electric power in large installations is less than \$200/kw. It is believed that small solar engines and generators can be built for a comparable continuous-operation cost of about \$1000/kw. This cost is low enough to justify research and further study.

Fractional-kilowatt steam engines are inefficient, but small Stirling hot-air engines of good efficiency have been developed [1–3].[2] They involve no water problems and could be built and tested quickly without large capital investment.

As a general rule, small engines are avoided because of the larger capital cost and labor cost per unit of power. In the present case, the engines have to be small because the focusing collectors are limited to small size due to the fact that they must be moved continuously to track the sun. The need for solar engines is urgent because of the impending shortage of power, the increase in population and overcrowding of our cities, and the need to reduce the pollution of our air.

Solar Collectors

Stationary flat-plate collectors of solar radiation are cheaper than focusing collectors, and they utilize both diffuse and direct radiation. Because they are stationary, they can be large in area and thus operate large engines. However, they do not ordinarily give temperatures above 100 C, which limits the engines to rather low efficiencies, and cooling is difficult. The large area of the heated transparent covers of the collector leads to large heat losses.

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[1] Between the time this article was written and the time of publication we were informed of the death of Dr. Daniels, on June 23, 1972, following an extended illness.

Based on a paper contributed by the ASME Solar Energy Applications Group.

[2] Numbers in brackets designate References at end of article.

Movable focusing collectors are more expensive, and they cannot use the diffuse radiation from the sun, but they easily give temperatures of 500 C (and higher) and a high efficiency of conversion into mechanical or electrical work. They have advantages over fixed flat-plate collectors in that the area of the heated target is small and heat losses are low, in spite of the higher temperature, and in that they maintain a high intensity of solar radiation even when the sun is low in the sky in winter time and early and late in the day because the focusing collector can be kept continuously at right angles to the sun's rays.

The higher temperature of the focusing collectors gives an important advantage in cooling and can permit air cooling rather than water cooling.

A great disadvantage of the focusing collectors is that for easy shipment and manipulation and for resistance to strong winds they are limited to small size, perhaps 6 ft in diameter. A collector of this size with an area of 28 sq ft cannot now operate a heat engine of more than about $\frac{1}{2}$ kw mechanical power. This handicap of small size applies also to the equipment which is operated by the small engine, such as water pumps and electrical generators.

The relative advantages (+) and disadvantages (−) of the focusing collectors are summarized in Table 1. In the last line, it is pointed out that some of the advantages of the movable focusing collectors in using the solar radiation when the sun is low in the sky can be achieved in flat-plate collectors by tilting them at intervals corresponding to the change of seasons. Also, the horizontal focusing collectors aligned along the east–west axis can be made larger than the circular collectors, but the temperature at the focus of the radiation is considerably less.

For the present discussion of solar power from small engines, it is believed that the focusing collectors are better than the flat-plate collectors. Suitable parabolic focusing mirrors of plaster and cloth have been developed and tested. They can be made in the field with a few man-hours of work. A parabolic mound of wet sand covered with a thin layer of concrete is made by rotating a parabolic knife edge around a central pipe stuck in the ground. With this mound, it is possible to make an indefinite number of parabolic shells. The mound is greased and covered with plaster of Paris containing a retarder which spreads out the evolution of the heat of crystallization over a longer time interval and reduces the temperature and thermal expansion. Cheap burlap cloth is spread over it, and the outer edges are curled around a circle of thin-walled steel tubing laid over it. More plaster is added, and after setting the shell is removed. Improved focusing is achieved by lining with a second layer of plaster scooped out with a revolving parabolic knife edge. After drying, the shell is painted with shellac and covered with 3M Chrome No. 5400, a reflecting polyvinyl fluoride covered with a pressure adhesive costing 50 cents/sq ft. A sample of this material has been exposed to outdoor sunlight continuously (in Wisconsin) with no appreciable deterioration. It reflects 86 percent of the sunlight. These 6-ft mirrors, with an area of 28 sq ft, weigh about 100 lb, and the cost of materials is about $25 at retail prices, exclusive of labor.

TABLE I

	Flat-plate collectors	Focusing collectors
Operation	Stationary (+)	Moving ( )
Efficiency	Large (+)	Small (−)
Heat losses	High (large area) ( )	Low (small target) (+)
Temperature	Low (−)	High (+)
Efficiency $\frac{T_2 - T_1}{T_2}$	Low (−)	High (+)
Cooling	Difficult (−)	Easy (+)
Solar radiation	Direct and diffuse (+)	Only direct (—)
Solar radiation	Sun high in sky (−)	All day and winter (+)
Capital cost	Low (+)	High (—) (?)
Labor cost	Low (+)	High (—) (?)
Intermediate	(Tilted stationary)	(Cylindrical E–W)

Spun aluminum shells $\frac{1}{16}$ in. in thickness did not give sufficiently sharp focus. With a large capital investment ($120,000), the focusing collectors could be stamped out of sheet aluminum or iron-like automobile bodies. They would be cheaper and lighter and suitable for easy packing and shipping, and they would probably give better focusing.

Engines

Ericsson operated a small solar Stirling hot-air engine 100 years ago.

Farber [1], at the University of Florida, has operated a $\frac{1}{2}$-kw Stirling hot-air engine remade from a small internal-combustion engine used for operating a lawnmower. He measured a 10 percent efficiency in going from solar radiation to mechanical energy. These engines could probably be mass-produced at a cost of about $15 each.

Beale [2], at the University of Ohio, has demonstrated a small free-piston Stirling engine of good efficiency.

Eibling and Finkelstein [3] demonstrated a small Stirling engine provided with a quartz window so that the heat from the focused radiation is liberated inside the engine, thus avoiding the "bottleneck" of a slow heat transfer across the end of the head of the engine cylinder.

The vibration of the engine, mounted over the focusing collector, is quite violent. Most of the Stirling engines need to be started by hand, which is a serious handicap in a remote area. These difficulties can probably be overcome.

There is a possibility of developing hot-air turbines or high-boiling vapor turbines which will operate at temperatures over 200 deg. The focusing collectors can deliver heat to a target with an efficiency of about 65 percent and raise the temperature to about 500 C on a target about 3 in. in diameter.

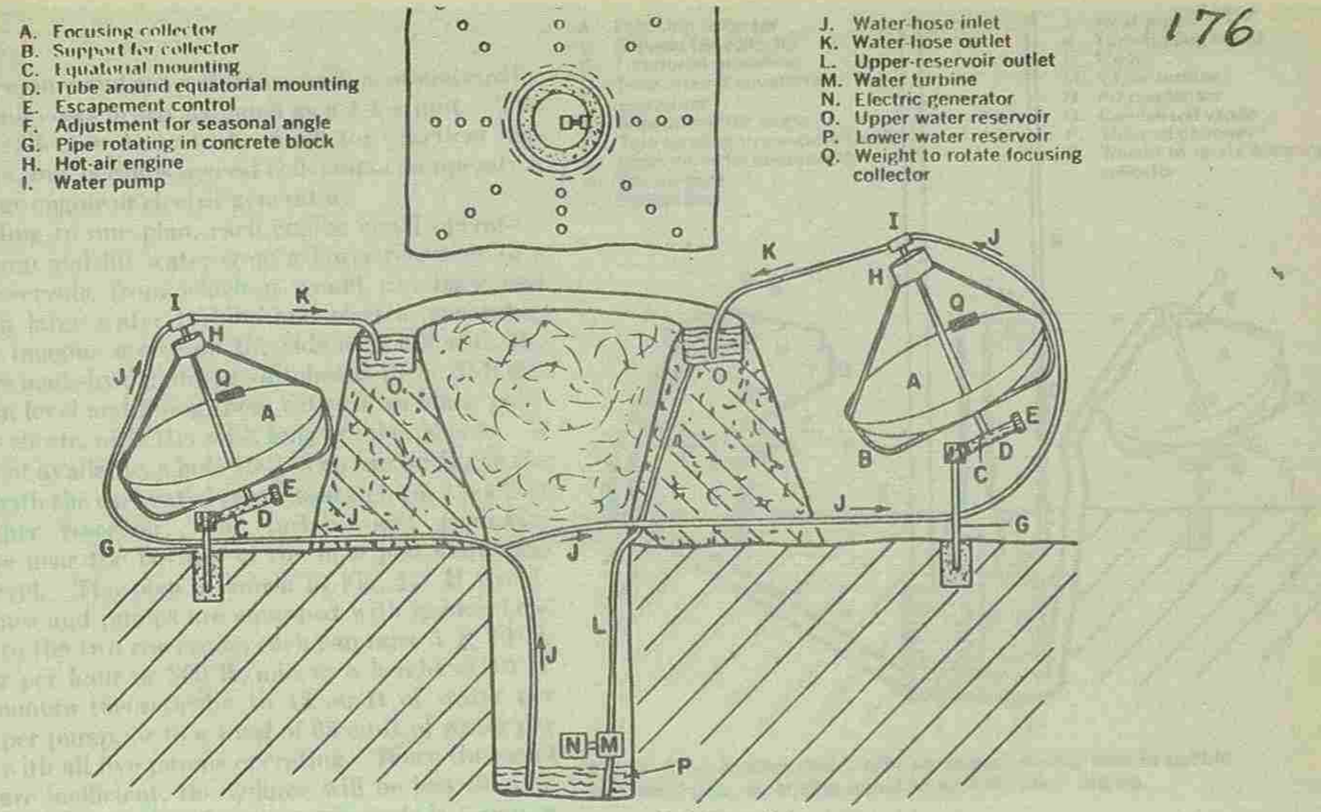

Fig. 1 Solar engines, pump, and water reservoirs operating larger water turbine and dynamo.

Tracking the Sun

Several automatic or semiautomatic devices have been developed for keeping the sunlight focused on an engine. They involve thermal expansion and contraction of a lever by sunlight and shade, photocell operation of an electric motor, a controlled leak, a clockwork mechanism, or a falling-weight pendulum and escapement wheel.

A promising device for tracking has been developed by Choudri [4] in which two bellows actuate a cable wound around the central axle of the equatorial mounting. The bellows are filled with water at two different levels. The rate of turning is controlled by the heating of alcohol by the sun, which increases the vapor pressure and actuates a bellows which shuts off the flow of water.

The best approach would be an equatorial mounting pointing north with a counterpoise at the top of the collector. It falls to the position at the bottom at a rate (equal to the sun's movement) which is controlled by an escapement wheel and pendulum. Sometime between sunset and sunrise, an operator travels over the assembly of collectors and rotates the collector 180 deg from facing west to facing east. In certain areas of the world where labor is cheap, it might be economical to avoid the capital cost of an automatic tracking device and keep the collectors facing the sun by manual operation, going from one collector to many others in a repetitive path.

The solar engines can operate water pumps or they can run electric dynamos for charging standard automobile storage batteries. They can be charged individually and discharged in series to give a higher voltage. There are complications in keeping many small generators of differing speeds connected together.

Costs

A 6-ft collector, with an area of 27,000 sq cm, intercepts 38,000 cal/min when the normal solar radiation intensity is 1.4 langley. At 65 percent efficiency, it delivers 25,000 cal/min or 1.5 million cal/hr to a small target and easily produces a temperature of over 400 C. This amounts to 1.8 kw of heat, which at a 15 percent engine efficiency produces mechanical power at 0.27 kw. Further conversion in an electric generator at 75 percent efficiency gives 0.20 kw of electrical power and 1.6 kwh of electrical energy in 8 hr of sunlight.

If a collector and tracking device cost $25 (for materials only), an engine costs $15 (mass-produced), and an electric generator $20 (similar to an automobile generator), the total capital cost for a $\frac{1}{5}$-kw unit would be $60. This amounts to $300/kw capital investment compared to $200 for large conventional power plants, but the solar investment produces kilowatt-hours only while the sun is shining, and to put this on a comparable basis with fuel-fired power plants, the cost of $300 should be multiplied by a factor of 2 or 3 depending on the load factor of the conventional power plant. Considering labor costs and other factors, an estimate of $1000/kw would seem to be reasonable.

Assuming continuous operation of 8760 hr during the year and depreciation and interest charges of 10 percent per year, the capital cost is 10,000¢/8760 or about 1.1¢/kwh. If a man is paid $1 an hour for the morning adjustment of the collectors and he services 200 collectors per hour and they produce electrical power for 8 hr during the day, the operating labor cost is (100¢)/200/5 × 8 = $\frac{1}{3}$¢/kwh. On the basis of these assumptions, electrical power might be produced at a cost of about 1.1¢ + 0.3¢ or 1.4¢/kwh. In some areas, the labor costs would be much less than $1/hr and 0.3¢/kwh. In industrialized countries, on the other hand, the labor costs might be three times as much. The assumption that one man would be able to service only 200 collectors per hour is purely arbitrary.

Small engines and generators are inefficient and costly. A $\frac{1}{5}$-kw unit costs nearly as much as a 1-kw unit. The focusing collectors have to be small for practical manipulation, but perhaps several collectors can operate a single large engine or electric generator.

According to one plan, each engine could operate a small pump and lift water from a lower reservoir to a higher reservoir, from which it would run back and operate a large water turbine and electric generator. One can imagine a site on the side of a hill with the reservoirs made by digging two ditches at 10- or 20-ft difference in level and lining them with cheap black polyethylene sheets, or better with butyl rubber sheets. If a hill is not available, a hole 10 ft deep can be dug in the ground with the excavated earth used to form a pool for the higher reservoir. The turbine and generator would be near the bottom of the hole just above the water level. The plan is shown in Fig. 1. If five $\frac{1}{5}$-kw engines and pumps are equipped with garden hose leading to the two reservoirs, each can raise 5×10^4 lb of water per hour or 800 lb/min to a height of 10 ft. This amounts theoretically to 13 cu ft of water per minute per pump, or to a total of 65 cu ft of water per minute with all five pumps operating. Since the small pumps are inefficient, the volume will be less than 65 cu ft. If the retention time in a reservoir is 1 min, a reservoir of 65 cu ft would be sufficient. This can be visualized as a circular pool $6\frac{1}{2}$ ft in diameter and 2 ft deep at the bottom of the hole in the ground. It must be emphasized that in the barren country where these small engines might be introduced, water is very difficult to obtain and keep.

A second possibility is to store heat in large central underground insulated pebble or gravel beds (or blocks of ceramics) and bring in streams of heated air by passing it through small pebble beds or black honeycomb ceramic structures at the focus of each focusing collector. There could be two of these pebble beds, one collecting heat from the small collectors while the other previously heated pebble bed would have cold air blown through it to supply heat for operating a single large engine.

Again, taking five solar collectors each delivering 25,000 cal of heat per minute to the target at 500 C gives 125,000 cal/min. It would be difficult to transport this hot air through long well-insulated pipes without having severe heat losses. To transport 125,000 cal of heat per minute with cold air heated to 500 C would require an airflow of about 35 cfm. If the pebble beds were alternated every hour, a storage capacity of 7.5 million cal would be required. This could be supplied by 30 liter (1.1 cu ft) of magnesium oxide spheres or gravel with 33 percent void spaces (density $MgO = 3.65^{-1}$ gcc^{-1} sp. ht. = 0.209 cal/day) cooled from 500 deg.

Instead of using two pebble beds for collecting and using the heat, it would be preferable to use only one and to insert a large heat pipe which would operate a high-temperature vapor turbine as indicated in Fig. 2. Then cold air would not have to be pumped through the heated pebble bed. It may be difficult to remove heat fast enough from the pebble bed through the heat pipe.

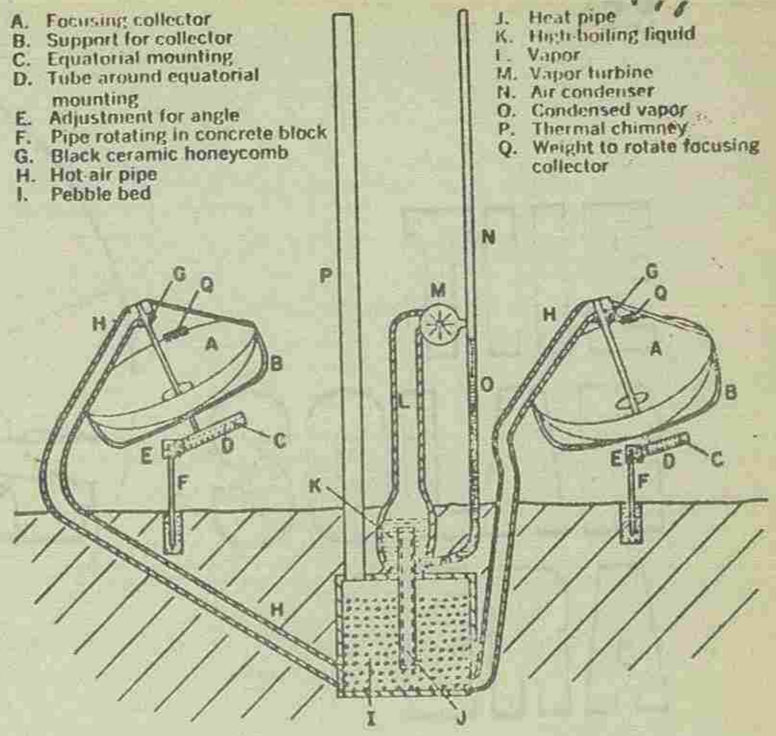

Fig. 2 Solar heaters 500 C with air stream storing heat in pebble bed. Heat pipe vaporizing liquid to operate vapor engine.

Storage of Power

If 65 cu ft of space is required for a water reservoir at an elevation of 10 ft to store 1 kw of power for 1 min, 93,000 cu ft would be required to store it for 24 hr. This is too large a reservoir to be practical.

For the storage of heat in pebble beds as previously described, it would take a volume of 1.1 cu ft to store a kilowatt-hour of electric power or 7.7 million cal of heat, assuming an engine of 15 percent efficiency and a dynamo of 75 percent efficiency, or about 27 cu ft to store 24 kwh of power.

Storage batteries may be operated by the 0.2-kw d-c dynamos attached to the Stirling engines on each focusing solar collector. Standard lead-acid storage batteries are available, but a longer-lived and hence cheaper storage battery is needed. Exploration of a homogeneous reduction-oxidation storage-battery fuel cell is underway.

Another way of storing power is to produce hydrogen by the electrolysis of water using the small d-c dynamos. The technology of this highly efficient operation has been fully developed. The hydrogen can be used for operating internal-combustion engines or it can be used with a 60 percent efficiency in fuel cells. It can be stored in reservoirs and transported through pipelines. Perhaps the pipelines now carrying natural gas can be used for carrying hydrogen when in the future the reserves of natural gas become exhausted. Research should be directed toward finding a chemical which will take up hydrogen reversibly for storage and transportation.

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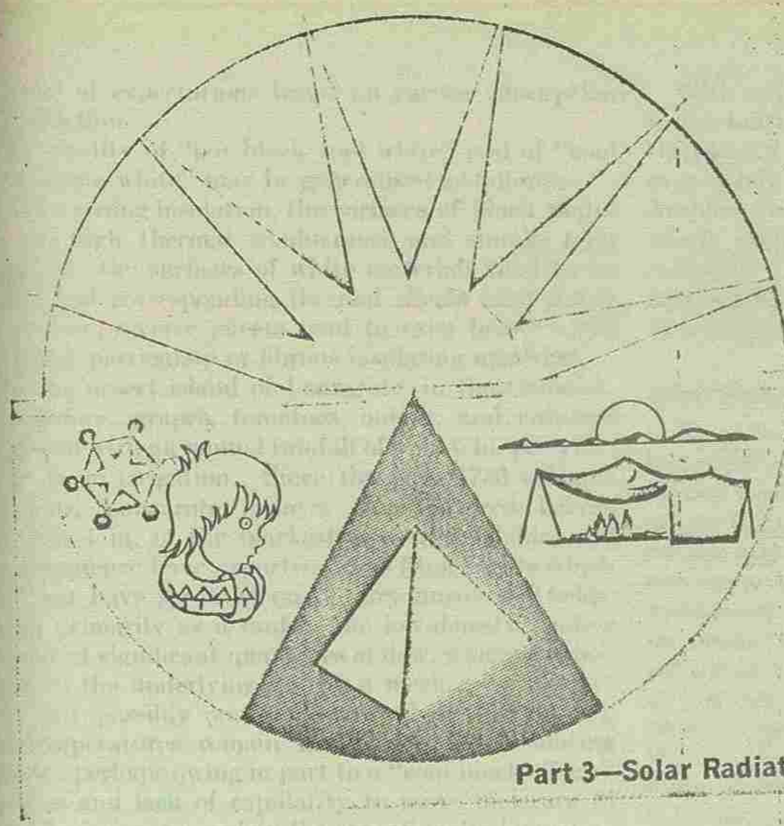

THE SOLAR ERA

Part 3—Solar Radiation: Some Implications and Adaptations

We are racing through fossil fuels, approaching limits of hydroelectric availability, and creating miniature suns. It is time to ask: Are obsessions concerning transmissible energy, plug-in convenience, "economics of scale," and conventionality retarding direct and effective use of solar energy? Here are some related thoughts and observations.

HAROLD R. HAY

"If man's ingenuity through the years had been directed to the utilization of solar energy instead of to the development of devices to consume fossil fuels, it is quite conceivable that we might today have a solar economy just as effective and efficient as our fossil-fuel economy. Ultimately, man will probably be driven to turn to the sun" [1].[1]

During the seven years since these challenging thoughts appeared in a survey of the energy resources of the future, environmental deterioration has increased the impetus toward solar orientation, but as yet there has been no major advance in that direction.

In marked contrast to man, nature has been an efficient gatherer and user of low-level solar energy for eons of time. Hydroelectric power, fossil fuels, habitability of polar countries, and much of life in all its forms are consequences of radiation collection by evaporating and circulating oceans. In fact, animal life as we know it owes its existence and development to adaptation to low-level solar effects. When animal life left the relatively constant temperature of the sea—and its UV-filtering effect—adaptation was required for the wide diurnal temperature range, drying winds, and broader radiation spectrum. Convenient rocks formed protective roofs and walls which served as radiation shields and offered, through heat capacity, lower daytime and higher nighttime temperatrues. This adaptation, when rediscovered by man, resulted in a high degree of thermal control in houses made of earth, stone, or bricks. Man's ultimate achievement with capacity insulation was in the pyramids, the centers of which have nearly constant temperature throughout the year.

To reduce construction costs of capacity insulation, a water-shell structure is under investigation; it has possibilities for thermal comfort comparable to that protecting life in the sea and in amniotic fluids.

Sea-emerging animal life found white rocks cooler both day and night than black ones; thus life became responsive to effects of radiation absorption, reflection, and emission. This responsiveness was neurally reinforced upon man's walking on, or picking up, stones; eventually, he developed black-surface absorbers and white-surface reflectors of near-perfect efficiency. These were generally applied over conventional materials of high thermal conductivity; the impression grew that subsurface thermal effects corresponded to surface color.

Coevally, our emerging sea life may have taken refuge under black, spumaceous volcanic rocks and found them cooler day and night than nearby white pumice. Data are insufficient, but observations indicate that thermal effects under insulating materials may be the

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[1] Numbers in brackets designate References at end of article.
Based on a paper contributed by the ASME Solar Energy Applications Group.

opposite of expectations based on surface absorption and reflection.

The duality of "hot black-cool white" and of "cool black-warm white" may be generalized as follows:

Under strong insolation, the surfaces of black materials of high thermal conductance and storage tend to be hot, the surfaces of white materials tend to be cooler, and corresponding thermal effects exist below the surface; reverse effects tend to exist below white and black particulate or fibrous insulating materials.

On the desert island of Lanzarote, in the Canaries, watermelons, grapes, tomatoes, onions, and potatoes are grown with an annual rainfall of only 6 in. per year. There is no irrigation. Since the 1730–1736 volcanic eruptions, Lanzarote farmers have covered barren soil with 4 in. of the blackest cinders available, and in consequence have exported crops from plants which could not have sprouted on the dry uncovered fields. Acting primarily as a mulch, the low-density cinders also collect significant quantities of dew, which is transferred to the underlying soil by a mechanism not yet clear, but possibly one of downward distillation [2]. Soil temperatures remain low under the insulating cinders—perhaps owing in part to a "cool-black effect." Coolness and lack of capillarity to move moisture to the surface seem to explain the exceptionally low evaporation from soil below the cinders.

Cool Black

Discussion of the cool-black effect caused Greek agricultural experts to consider it the first substantial justification for the 2000-year-old practice in Thessaly of burning wheat fields soon after early summer harvest. Throughout the world agricultural specialists have deplored this practice of burning straw, yet the objections cited (destruction of soil bacteria, loss of stem and leaf nitrogen, and wastage of a soil conditioner) were found invalid upon further study. Retaining validity within some regions is the need for the straw in erosion-control, and its possible industrial or low-grade fodder use.

The Greek agriculturalists had been puzzled by earlier emergence, faster growth, and greener color of plants in rows where straw had been piled more thickly prior to burning. Fertilizing effects were discounted because the soil was not deficient in ash minerals. Soil moisture retained by a cool-black effect of insulating ash could account for the growth differences. Another solar radiation phenomenon, however, was also involved. The impact force of early fall rains crushes the insulating ash to a thermally conductive pigment. Acting as a radiation absorber, this black pigment causes underlying soil to be warmer during cool weather. In nature, therefore, benefits may accrue from both hot-black and cool-black effects.

Supporting data for the cool-black effect stem from Australian studies showing that dark cattle exposed to strong insolation have lower rectal temperatures than lighter colored animals [3]. The explanation appears to be the fourth-power radiation law: Although the black hair tips of sheep had surface temperatures of 190 F, reradiation and induced convection dissipated the surface heat and served as an "automatic compensating mechanism" [4].

With native wisdom derived from a thousand years in the hottest desert in the world, the Tuareg tribe in the Sahara wears a thick blue or black outer garment over white cotton undergarments. Nomads of the Arabian desert live under a cool brown or black tent which excludes infiltration of heat-generating solar radiation. The dark color of the goat- or camel-hair tent results from animal adaptation for survival under intense solar radiation.

Warm White

To account for the white Australian cattle having higher body temperatures, a warm-white effect is postulated on the premise that though 60 percent or more of incoming radiation might be reflected and another portion absorbed and reradiated at the hair tips, the remainder is reflected from hair to hair in a downward course. Radiation converted to heat while within the insulating hair or upon reaching the skin would act to raise body temperature. It is common practice in hot dry countries to slaughter, in early summer, those young goats having much white coloration. White animals are more prone to sun scald during summer months than are dark-colored ones.

In the Arctic, the heat-collecting effect of white uniforms resembling fur was inconclusively reported by the military. A white synthetic pile on a black backing was covered by a white translucent film to prevent wind spillage of heat from between the white fibers. Radiation heat gain was not reported, nor was it clear if reflection and absorption of body-heat radiation accounted for the improved efficiency over the standard uniform. In this uniform, temperatures dropped from 90.5 to 86.5 F in 50 min versus 120 min for the white uniform [5]. Experiments with birds showed a reduced metabolism resulting from irradiation of white plumage; in these tests, black plumage had a greater effect [6].

In Scandinavian countries, low ambient temperatures are countered with clothing which leaves the hands and head as receptors for UV radiation vital to activate precursors for vitamin D needed for bohe growth. Light reflection inward to the skin through the hair of "towhead" children, possibly supplemented by a fiber optic effect, may assure required UV absorption for bone development. Once this has been attained, it is not unusual for northern Europeans to develop moderate hair pigmentation, which may again be lost at an advanced age when bone weakness tends to occur. Applied to the dominant white coloration of Arctic animals, this theory would somewhat reduce the importance of white as representing adaptation for protective coloration.

One can also speculate about pigmentation as a genetic adaptation to solar radiation in the tropics. There, the hair of people subjected to strong insolation is normally black. In part, this may be to keep the head cool; over less hirsute portions of the body, it may act to partially absorb and dissipate radiation. As a heat collector, black skin is contraindicated, but it serves as a UV screen to prevent skin cancer. To offset the high thermal load induced by protective pigmentation, black skin may have more evaporative cooling provided by a greater number or activity of sweat glands per unit of area than has northerly adapted, sparsely pigmented skin.

If further studies establish the validity of the cool-black-warm-white hypothesis, the implications are many. It has been reported that metal surfaces under some white paints exposed to strong solar irradiation have temperatures higher than anticipated; paint porosity may be a factor. White high-density aggregate for asphalt roofs may be less desirable than black (acid-free) coke or similar materials. Loose black pile or boucle weaves may be cooler than denser weaves of lighter colored fabrics for hot dry regions.

A Lanzarote practice simultaneously uses reflectors and absorbers for human comfort. Stone houses are painted white to effect reflective insulation. Black low-density stone around the window opening as well as a thin layer of black cinders in lieu of a lawn are used to eliminate heat gain and glare from reflected radiation. In contrast, lack of adaptability by newcomers to desert regions causes unnecessary discomfort and expense.

Negative Energy

Sleeping patterns reduce man's consciousness of the equality of nocturnal radiation with solar radiation in the terrestrial diurnal energy balance. Natural "negative energy" has great potential for reducing our paradoxical use of air conditioners to convert energy into heat to produce cooling. Nature is less obtuse.

For natural air conditioning of man-made structures, economic heat storage is a prerequisite, with water the logical medium. Ceiling ponds are capable of maintaining comfortable temperatures throughout a normal year, in Phoenix, Ariz., without supplementary heating or cooling devices [7]. These ponds collect and store winter solar heat during the day and release it into rooms at night. In summer they collect and store infiltrated and internally generated heat during the day, then radiate it to the night sky. Movable insulation panels over the ponds operate as a thermal valve directing heat flow to produce desired thermal effects.

Because natural air conditioning works with the climate—not against it—the system flexibly utilizes and controls radiation absorption, reradiation, evaporation, and air movement. Winter heating results from exposing the ceiling ponds (enclosed in transparent plastic bags) to solar radiation. The room remains above the maximum ambient temperature. During nearly all of April and October, heat capacity alone holds room temperatures in the comfort zone—essentially within the comfort range obtainable with thermostatic control of conventional heating and cooling devices alternately used night and day in houses lacking heat-capacity insulation.

For summer cooling, nocturnal radiation is adequate with temperatures as high as 100 F; the ponds cool to the night sky although heat is received from both the underlying room and the overlying air. Radiation cooling plus evaporation of water flooded over the plastic-enclosed ceiling ponds maintain room comfort until outdoor temperatures exceed 105 F. Electricity is not needed until daytime temperatures surpass 105 F. Then a fan coil is adequate until temperatures rise over 110 F, whereupon additional use of a roof-pond blower will assure comfort during periods of relatively low dew point. High dew points with temperatures of 100 F require use of both the fan coil and the pond blower [7, 8].

The fan-coil unit transfers room heat to water circulating in three ponds which form the ceiling roof of the Phoenix room. The air blower is needed especially during hot humid periods when radiation heat loss is minimal and evaporation is retarded. The six adaptations to natural forces are used to develop a flexible natural air conditioning system requiring only minimal supplementary energy and devices in hot dry regions—none where comfort standards are not so narrow as those in the U.S.

Previous efforts to use natural forces with commonplace building construction failed to provide economic heating and cooling. Natural air conditioning calls for unconventional building design. Ceiling-pond economics are made favorable by deducting normal ceiling and roof costs from those of the ponds and movable insulation. The basic architectural style is indigenous to arid regions throughout the world—the result of thousands of years of man's adaptation to a highly adverse climate.

New plastics have greatly increased the feasibility of economic use of solar radiation. Most of the earlier forms of insulation would have to be hermetically sealed to prevent moisture uptake and loss of insulating value if used over ponds or exposed to rain. Established sandwich-panel technology using cellular plastics permits new and highly desirable types of construction—including exterior thermal insulation and internal heat-storage materials.

The aforementioned transparent-plastic pond bags and the underlying black liner for radiation absorption and for roof waterproofing may be of the films listed in order of increasing cost and resistance to deterioration by solar irradiation: polyethylene, polyvinylchloride, and polyvinylfluoride (PVF). A continuity of improved formulations and new resins assures better film life and economics for many applications of solar radiation.

Solar Stills and Water Heaters

The most satisfactory experience with solar stills to date has been with glass-covered types developed 100 years ago. Despite considerable research in recent years, there has been no improvement in yield and only a minor reduction in construction costs. Nonetheless, solar stills remain the cheapest means for desalting quantities of less than 50,000 gal of saline water per day in areas of reasonable sunshine. Production cost of about $3.50 per 1000 gal produced in a community still results, in substantial part, from a high capital investment. Such a system, which frequently occupies land better used for other purposes, necessitates dual piping for distilled water and for a second supply to meet nonpotable needs. It results in serious wastage of a costly product. Faced with such disadvantages, use of solar stills has been severely circumscribed.

Recently it was proposed that the initial cost of solar

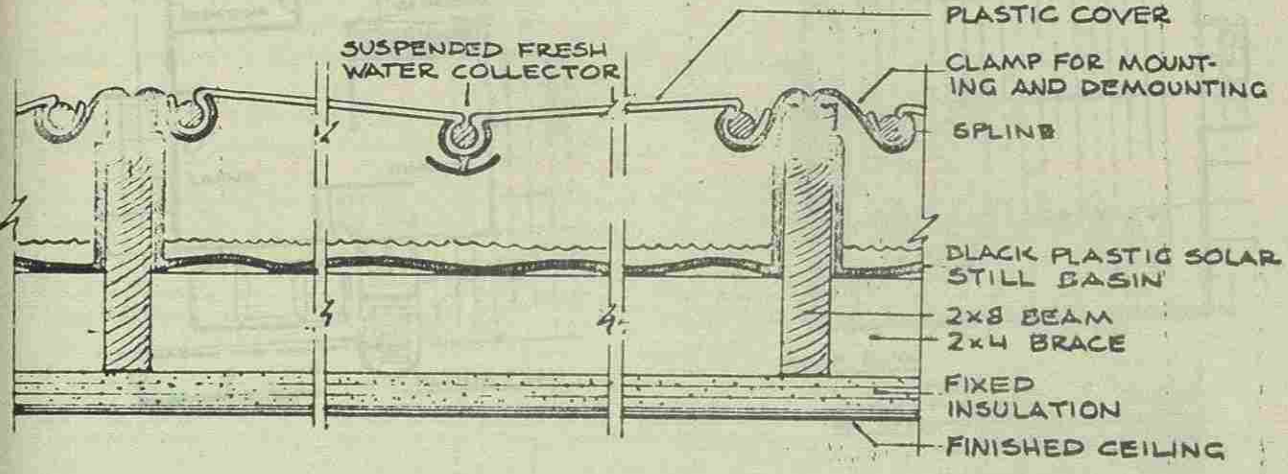

Fig. 1 Plastic rooftop solar still for desalination of water.

desalination might be fully offset by using a still for the ceiling and roof of a building [9]. Modular stills, producing 25 to 30 gal/sq ft/year of distilled water, would be placed between ceiling beams; this would simplify the leveling to obtain shallow brine depths conducive to high yield. Insulation under the still, also essential for high yield, would form the ceiling. Several still designs are available with costs approximating those of conventional roofs. Plastic pipes and fittings would be used not only for the stills but also for bringing saline water to the building and for conducting concentrated brine away in a sewerage system.

Plastic is the preferred cover material for roof stills. The inherent safety hazards of glass almost preclude its extensive use on roofs in densely populated areas. Even with costly framing, which would make it uneconomic for desalination, some breakage of glass must be expected during construction, use, and maintenance. Glass shards might pierce the solar-still liners and cause flooding of an underlying room. Building codes and insurance rates could prove restrictive for glass-covered roof stills.

Fig. 1 illustrates a new solar-still design that is adaptable as a roof and is expected to correct many shortcomings of previous stills. The rigid basin, of molded black ABS resin, would be supported by 2- by 4-in. braces between ceiling beams. The transparent cover film is shown fastened in S-clamps engaging protrusions and seals on the sides of the stills. Seals of adjacent stills would be parts of an extrusion covering the beam and waterproofing the roof. The weight of the center-suspended condensate collector contributes to the vapor seal and shapes the V-cover so that distillate drains to the collector. Stretching the cover tighter at one end produces slope for drainage of condensate and of rain. Each is removed in tubing slipped over portions of the collector and each is conducted to separate storage.

Advantages of this design, other than eliminating glass-cover hazards, include:

- Prefabrication
- Quick assembly
- Ease of access to the basin for annual cleaning of salts, if required
- Cover replaceability, if cleaning or patching is needed
- Minimal vapor leakage at seals
- Division of the cover into two panels, thereby reducing wind flutter and film embrittlement.

Accidental cover damage would, at most, allow rain to drain into the condensate collector. Annual inspection and servicing charges might offset the lower capital cost and interest resulting from crediting usual ceiling and roof costs. Product-water costs are not expected to differ greatly from those of desalination at a community distillation plant.

Previous economic analyses of solar stills having covers of 10-ft-wide 4-mil PVF used film prices ranging from 27.6 to 44.3 ¢/sq ft. These included high charges for special width and thickness, for sandblasting one side to produce wettability, and for shipment to distant islands. With 54-in-wide 1.5-mil untreated film costing only 3 to 3.5 ¢/sq ft, 2-mil thickness is about 4 ¢, and 4-mil PVF should sell for 8 ¢/sq ft if a substantial market for this thickness develops. A new liquid wettability treatment[2]—successfully used on plastic greenhouse covers—is claimed to last the life of the plastic and to cost less than 0.5 ¢/sq ft applied. On a wholesale basis, the price of 4.5 or 8.5 ¢/sq ft offsets the longer average life obtainable with single-strength B-quality glass costing 16 to 20 ¢/sq ft and having higher packing, transport, and breakage charges.

Sandblasted 4-mil PVF has given four to five years of service in large solar stills of a design which tended

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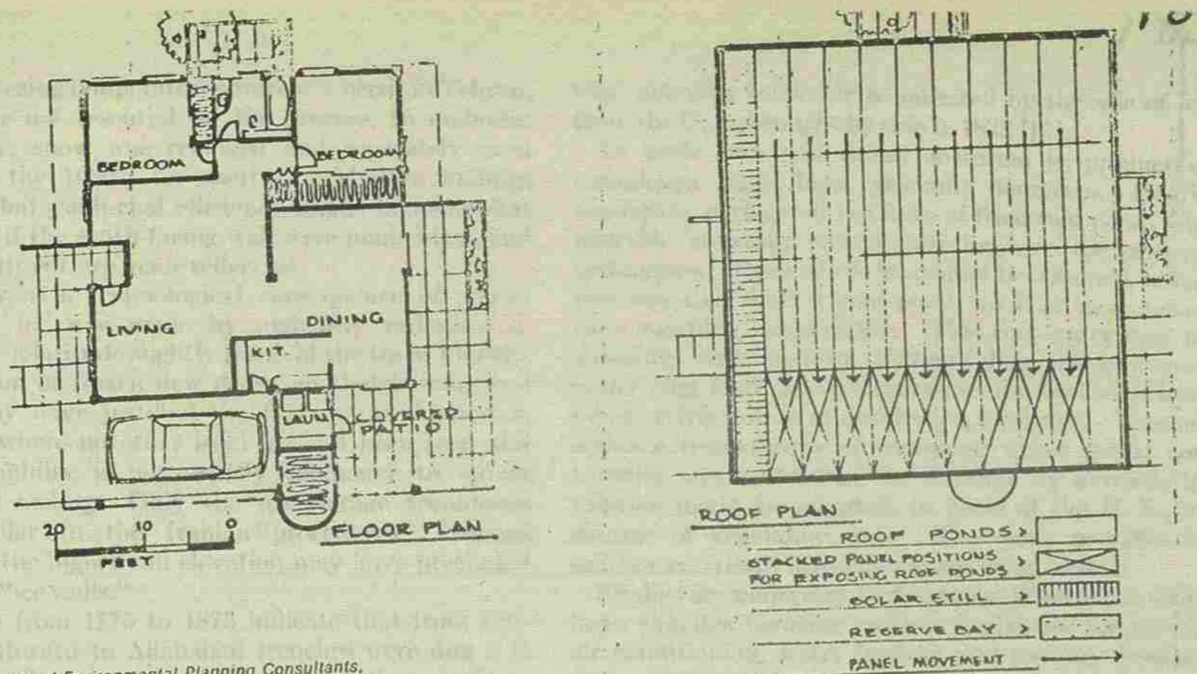
[2] Sun Clear, a product of Solar Sunstill, Inc., Setauket, N. Y.



Courtesy of Environmental Planning Consultants, San Luis Obispo, California

Fig. 2 Floor plan of naturally air conditioned house and roof plan indicating movement of insulation panels to expose roof ponds. Also shown: rooftop solar still and reserve bay usable as solar water heater.

to shorten film life by creating severe local stresses. Design factors sometimes caused failures after only one or two years. Because PVF still covers tend to yellow after four to five years of exposure, there is little need for a longer mechanical life unless UV inhibitors can reduce photodegradation. Elimination of abrasive wettability treatments and reduction of unsupported cover widths (to minimize flutter, crystallization, and wind damage) should assure a five-year life for either 4- or 2-mil film. A three-year service for a 2-mil V-cover, weakened by sandpapering and inadequately fastened, has already been demonstrated. PVF covers have produced the highest yields ever reported for large solar stills [10].

Fig. 2 illustrates the manner in which solar stills, solar water heaters, and natural air conditioning ceiling ponds can serve as a roof. Movable insulation panels retard nocturnal heat loss from these energy collectors. The same technology, and interchangeable parts, can produce cold water and ice.

Yakh-chals

We are reminded in a well-qualified engineering textbook that, neglecting evaporation, radiation to outer space could freeze water in shallow insulated trays when the ambient air temperature is 630 R or 170 F; back-radiation and moisture condensation from surrounding air greatly lower this temperature. Desert conditions are the most favorable for strong natural cooling [11].

Prevailing attention to the economic consequences of animal comfort is resulting in studies of natural thermal phenomena. The development of sun-shading devices for animals resulted in the observation that whenever possible the animals preferred the north shade of tall reflective walls. This response was related to radiation cooling from the south side of their bodies to the wall and reflection to "cold spots in the sky" at a right angle to the sun [12]. Later studies not only found that white sloped-toward-the-north surfaces are indirect daytime heat sinks but also that black, fully shaded, northerly oriented walls achieve surface temperatures higher than those of the surrounding air [13].

Natural air conditioning of rooms by daytime radiation to the cold sky has not been studied to the extent which seems justified. Although the lowest temperature in a cloudless sky is constantly changing its daytime position, this change did not vary greatly during the hot period of the day from 60 deg above the horizon at the location of the studies. Structures with windows sloped to take advantage of this cold sink might minimize heat load in polar-oriented rooms. Care would probably be needed to prevent excessive nighttime cooling.

Archaeological evidence exists that thousands of years ago "ice walls" were built in the deserts of the Middle East. These were mud walls running east–west, with basins on the north side in which water was frozen by nocturnal radiation. Known as yakh-chals, Fig. 3 [14], these devices are still used in remote parts of Iran. Their ancient shapes varied from single walls to three-sided high walls with the east–west wall five times the length of the end walls built at right angles to it.

Until 15 years ago, yakh-chals of different shape provided ice for Tehran. These were earth walls nearly 6 ft thick at the base and tapered to 8 in. at 25 to 30 ft in height. Frequently, two to four parallel walls 450 to 700 ft in length had end walls of lower height. Distance between the main walls was related to solar incidence to keep the enclosed ground shaded during the winter ice-making months. Air stratification caused temperatures to vary from that of ambient air near the top of the walls to subfreezing temperatures at ground level.

Clear water was flooded over the level area to gradually build up ice cakes of excellent clarity. These cakes were moved to covered pits where they were frozen into larger blocks by pouring on ice water. Although freezing temperatures and snow occur in Tehran, these were not essential for the process; to maintain ice clarity, snow was removed and separately used (early in the 1600s) for sherbets. Modern findings indicate that yakh-chal efficiency might be somewhat improved if the south-facing wall were made black and its northerly surface made reflective.

Possibly as a technological consequence of Aryan invasions, ice was made by night-sky radiation in Calcutta a latitude slightly south of the tip of Florida. Observation of frozen dew drops on thatch roofs and leaves may have justified the first ice production in Calcutta where no other local ice had been seen and where humidity is not usually conducive to strong nocturnal cooling. Only the ice storage techniques were similar to the Iranian procedures. Tropical rains and the higher sun elevation may have precluded use of the "ice walls."

Reports from 1775 to 1875 indicate that from Calcutta northward to Allahabad trenches were dug 2 ft deep and allowed to dry. Then insulation—such as sugar cane, corn stalks, or straw (a "black-looking" kind was "reckoned better for the purpose than wheat straw")—was added to within 6 in. of ground level. From December to mid-February winds were carefully observed. When they came gently from the northwest (even though warmer than the more humid prevailing air), unglazed shallow plates were placed in the trenches. Water was added in the plates to a depth expected to freeze, frequently 0.5 in., sometimes 1.5 in. Evaporative cooling lowered water temperature to a point where radiation caused freezing. Ice crystals appearing in some plates were thrown across the other plates as nucleation.

Ice was made in this manner when air temperatures were 43 or 47 F. The ice was carried to pits, pounded to a mass, watered, and frozen into a solid block. With the surface insulated and further covered by a thatched building, the ice lasted into the summer months. Some factories produced 120 tons per season; others made as much as 10 tons per night. That the economics was not very favorable is indicated by the sale of ice from the U. S., brought by ship in 1833 [15].

In both Iran and India, nocturnal ice-production techniques have been generally forgotten. Plastic insulation, perhaps in the form of fixed roof ponds and movable covering panels, can improve the ancient techniques. Even where ice cannot be obtained, radiation can cool shallow roof ponds 15 F or more below early morning temperature. This cool water may be naturally circulated by thermosiphon action around underlying food chests to serve as the best substitute for ice refrigeration in developing countries. Thermosiphonic recirculation of roof-pond water cooled nocturnally and covered in the daytime by movable insulation might be adapted, in parts of the U. S., for storage of vegetable crops. The same movable insulation can result in another space being heated.

Studies are underway to determine those areas which have climates favoring rooftop appliances for natural air conditioning, water heating and cooling, desalination, and ice production. Present plastics make these processes feasible for use in some climatic regions today. Experience gained in these areas, aided by further improvements in plastics and by additional studies of diurnal energy forces, will extend the range of applicability.

Extensive use of radiation-collecting and -dissipating devices in the American southwest is closer to realization. The disposition of the people, the need for new housing and cities, and the search by major companies for new markets may finally accelerate use of natural energy forces.

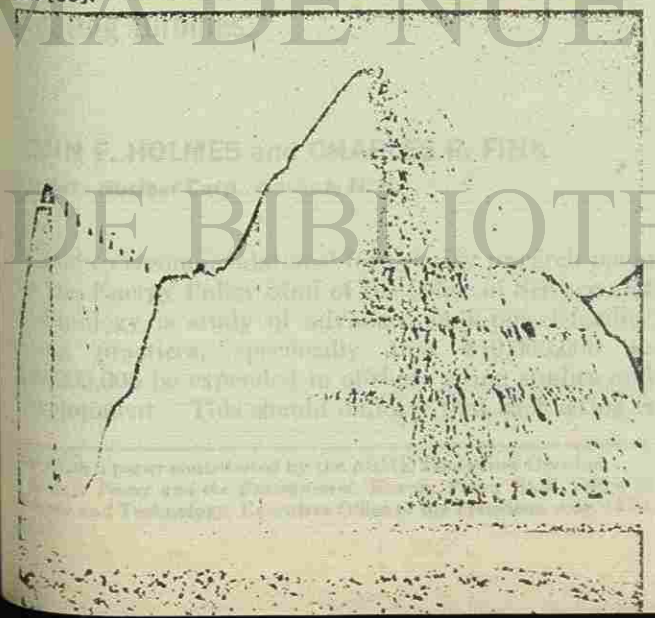


Fig. 3 Yakh-chal: Conical building (center) stores, below ground level, ice blocks cut from trough dug in ground and filled, in winter, with water that freezes during the night. Mud-brick wall (left background), built immediately south of trough, shields trough from sun [15].

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Tuned floating platform for offshore power facilities

Thermal discharges to the environment are common to fossil- and nuclear-fueled central power stations. Air discharges, too, are common—significant quantities of particulates and gases from fossil-fueled systems, small quantities of radioactive gases from nuclear—and each type of system has an impact upon its environs. Each of these problems is mitigated by offshore siting of bulk power facilities. Offshore siting also offers such distinct advantages as thermal enhancement of the waters to increase recreational and commercial values, and, a very important consideration along our west coast, earthquake-isolation of the bulk power facility. Not a practiced art, offshore siting brings with it new design considerations such as collision-avoidance and sea-driven platform motion effects on huge rotating turbines.

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Among recommendations[1] for priority research made by the Energy Policy Staff of the Office of Science and Technology is study of advanced bulk-power-facility siting practices, specifically that $10,000,000 to $20,000,000 be expended in offshore siting studies and development. This should indicate that such siting is not routinely accomplished. Optional techniques[2] include: (*a*) islands, existent and man-made; (*b*) bottom-mounted plants, floated to site and submerged or constructed in situ; and (*c*) floating platforms, tuned and un-tuned. Each has advocates and it is probable that each is a best solution in some certain specific circumstance.

The floating-platform technique is the subject of this article. It is shown in Fig. 1 with a 1000-MW(e) reactor power plant. Advantages include:

1 Construction of the hull and power-system platform is repeatedly accomplished by a skilled, stable shipyard workforce.

2 Dockside installation of the power system is also accomplished on a repeated basis by a trained, stable

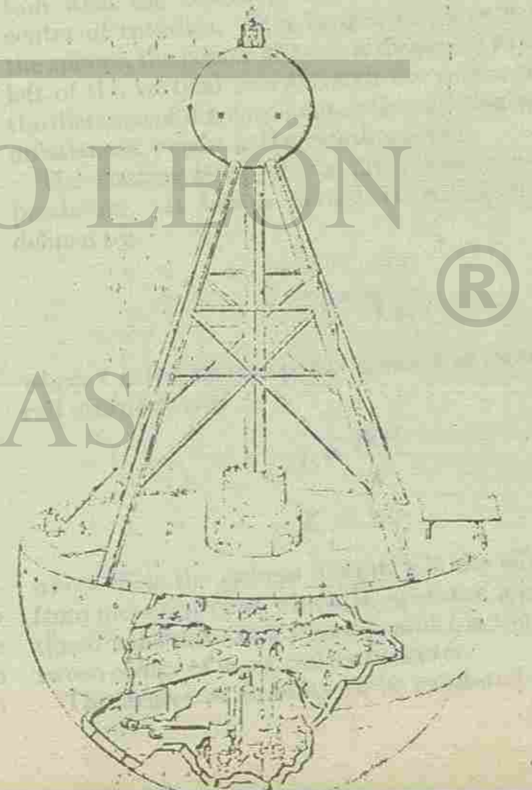


Fig. 1 Tuned-spherical-platform offshore bulk power facility.

Based on a paper contributed by the ASME Energetics Division.

[1] *Electric Power and the Environment*, Energy Policy Staff, Office of Science and Technology, Executive Office of the President, Aug. 1970, p. 44.

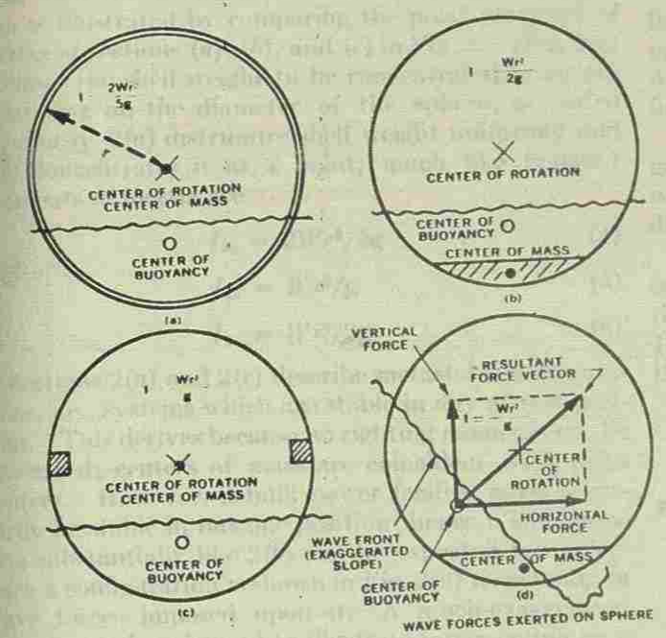


Fig. 2 Comparison of spherical buoys of different mass distributions.

workforce; this will increase the reliability of the operating system, a safety as well as an economic nuclear-power-plant consideration.

3 Mooring-site preparation is an economic operation vis-à-vis construction of island and subsurface offshore sites; a greater flexibility in site selection is also obtained.

4 The bulk power-plant facility is mobile, i.e., transportable; it can be towed to site, moved in response to changed requirements, returned to the shipyard to take advantage of technology improvements, etc.

Problems peculiar to the floating platform include:

1 Compliancy: The platform must be sufficiently stiff, i.e., noncompliant, that turbine-shaft misalignments (shafts can be as much as 200 ft long) do not cause turbine-generator failure.

2 Gyroscopic forces: Roll created by wave action must be made so minimal that side loads on the rotating turbine mass result only in negligible gyroscopic forces on turbine bearings and bearing mounts.

3 Mechanical loads: Platform motion in response to winds and waves must be minimal in order that loads on moorings and electric power transmission lines are not excessive.

The optimally noncompliant platform is a sphere. When used with a large secondary mass, the spherical platform can be "tuned" to have a natural roll frequency much lower than the exciting frequency of all conceivable waves; thus gyroscopic forces of consequence are eliminated and mechanical loads are minimized by constraining motion (heave) to be along the vertical axis (roll was removed by tuning). The spherical shape also assists in load reduction, since changes in draft due to acceleration and deceleration along the vertical axis are uniformly evidenced as buoyant-force changes equally applied around the circumference of the system.

Tuned Spherical Platform

To understand the principle of the tuned spherical platform, one must keep in mind these facts about a free-floating spherical body:

1 It has a center of mass whose location is determined by the system fabricator/designer.

2 It has a *fixed* center of rotation.

3 This center of rotation, the meta center, remains at the geometric center of the sphere *regardless* of how mass is distributed on or within the sphere.

4 All forces imposed on a free-floating spherical body operate inherently through, i.e., are vectored or directed through, the center of rotation.

Use can be made of the foregoing facts to design and fabricate an extremely stable, seaworthy platform for bulk power facilities. The sequence of sketches in Fig. 2 illustrates how.

Fig. 2(*a*) is simply a floating sphere with its weight uniformly distributed in its shell. Obviously, the centers of mass and rotation are coincident. In such a configuration the system is totally unstable with respect to roll. If a tangential force were applied to the sphere, it would begin spinning about the center of rotation; since the center of mass is at the center of rotation, no righting moment would exist and the spinning of the sphere would only be reacted and stopped by frictional forces at the sphere–air–water interfaces.

The foregoing implies that stability in roll is, in part, dependent on establishing a righting moment. Fig. 2(*b*) illustrates most simply how a righting moment is established. It assumes that the weight of the spherical shell is concentrated at a point on the circumference of the sphere. Two things happen: (1) The center of mass is displaced from the center of rotation to the surface of the sphere and (2) the sphere assumes a position with the center of mass immediately below the center of rotation. If a tangential force is applied to the sphere, the center of mass is displaced to the right or left of the vertical axis through the center of rotation; the distance of displacement is the righting arm and the unbalanced weight is the righting force.

The floating body of Fig. 2(*b*) acts as a compound pendulum. It has a period of oscillation which is defined by

$$T = 2\pi\sqrt{\frac{I}{K}} \tag{1}$$

where I is the system polar moment of inertia, K is the roll stiffness, and

$$I = \frac{Wr^2}{g} \tag{2}$$

$$K = Wl \tag{3}$$

where W is the system weight, r is the effective radius from meta center at which W operates, g is the gravitational constant (32.2 ft/sec²), and l is the distance between center of mass and meta center.

The degree of stability to be exhibited by a floating platform is, in part, determined by its period of oscillation; that this is largely determined by mass distribution is illustrated by comparing the polar moments of inertia of sections (*a*), (*b*), and (*c*) in Fig. 2. (Fig. 2(*c*) assumes the shell weight to be concentrated in an annular ring on the diameter of the sphere; as noted previously, 2(*a*) distributes shell weight uniformly and 2(*b*) concentrates it at a point, much like ballast.) Moments of inertia are

$$I_{3a} = 2Wr^2/5g \qquad (4)$$

$$I_{3b} = Wr^2/g \qquad (5)$$

$$I_{3c} = Wr^2/2g \qquad (6)$$

Sections 2(*a*) and 2(*c*) describe metastable configurations, i.e., systems which are stable in any at-rest position. This derives because no righting moments can be generated; centers of mass are coincident with meta centers. However, a bulk power facility must necessarily be stable in but one position; hence a configuration substantially like 2(*b*) can be expected to evolve. Such a configuration is shown in Fig. 2(*d*) responding to wave forces imposed upon it. A much-exaggerated wave-front slope is used to illustrate forces acting on a ballasted (tuned) sphere. Note that the spherical platform has not rolled in response to the wave front. The wave front has caused the center of system buoyancy to move, but the centers of system mass and rotation remain fixed; as a result, the system is translated vertically and horizontally but not rotationally. This in part is the case for the spherical platform. A non-spherical body, e.g., a boat or barge hull, would not react similarly to the passing wave front. The shift in center-of-buoyancy location would be accompanied by a shift in the meta center and hence in the meta-center-to-center-of-mass distance; roll would result.

In the intended application, a long period of spherical-platform oscillation is desired. This permits the platform to act as a "low-pass" filter of imposed wave forces. The platform, having a man-adjusted natural frequency longer than the forcing frequency of nature-adjusted waves, will, as a consequence, fail to be excited, i.e., rolled, by them. Platform stability will have been achieved through:

1 Selection of a platform shape having a fixed center of rotation.

2 Adjustment of the system center of mass such that desired roll stiffness (righting moment) exists.

3 Coincident adjustment of the system mass elements such that the system polar moment of inertia and roll stiffness define a system having a natural frequency not excited by seas to sea state 8.

Spherical-Platform Loadings

Roll is combatted in an offshore floating bulk-power-facility platform to ease platform compliancy constraints, to reduce gyroscopic forces on turbine-generator systems, and to minimize mechanical loads on moorings and power transmission lines.

Wave height and slope are the forcing functions on the platform. These are defined by Figs. 3 and 4. Significantly, a situation is described which indicates that a platform having a natural period of about 40 sec would be virtually unaffected by seas to sea state 8.

Reference-Design Tuned-Platform Nuclear Power Plant

A 1000-MW(e) tuned-spherical-platform offshore floating bulk nuclear power facility, as an example, lacks the additional complexity of system design that would be introduced by an ever-changing on-board fossil-fuel supply.

A boiling-water reactor system would be comprised generally as in Table 1. A pressurized-water reactor would have a similar total weight with component distribution as in Table 2.

A conceptual layout of the pressurized-water system is presented in Fig. 5; a mass-distribution approximation is shown in Fig. 6. Enclosed-system volume is 13M cu ft; a 300-ft-dia sphere weighing 66M lb houses the power system. Total bulk-power-facility weight is

Fig. 3. Maximum spectra of ocean waves.

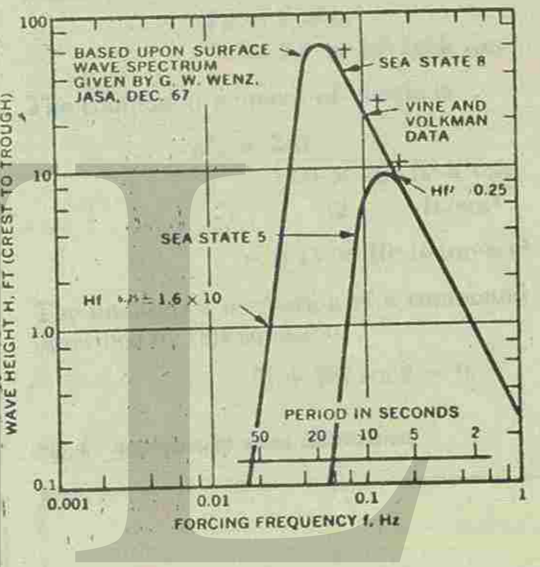


Fig. 4 Maximum slope angle of wave.

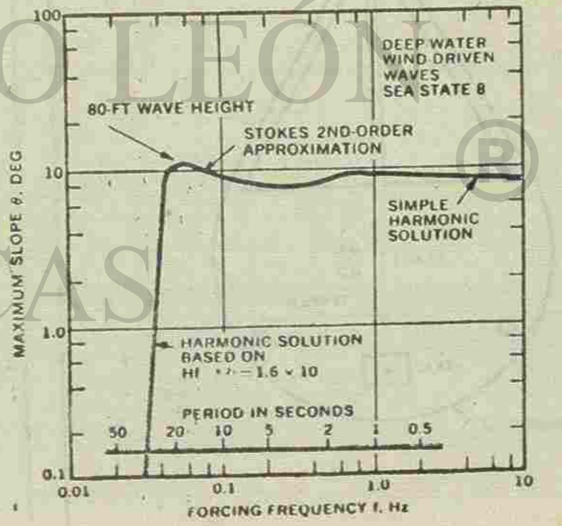


TABLE 1 Boiling-Water Reactor System

Subsystem	Weight (Millions of Pounds)
Reactor containment and pools	50
Nuclear steam-system equipment	3
Other reactor equipment	3
Turbine-generator equipment	23
Plant water	24
	103

85,000 tons; such an equipped structure is well within shipyard construction capabilities and is, in fact, smaller than many ships.

Reference-Design Roll Response to Sea States

The system compound moment of inertia with respect to the meta center must be determined before roll response can be calculated. Several simplifying assumptions are made:

1 Reactor and steam-generator mass is concentrated at a point on the axis 90 ft from the meta center.

$$\begin{aligned} gI_R &= 25 \times (90)^2 \\ &= 2.03 \times 10^5 \text{ ft}^2\text{-k ton} \end{aligned} \qquad (7)$$

2 Turbine-generator-system and condenser mass is concentrated in an annular ring at a 90-ft radius from the centerline and 70 ft below the meta center.

$$\begin{aligned} gI_{TG} &= m_{TG}(90^2 + 70^2)/2 \\ &= 1.24 \times 10^5 \text{ ft}^2\text{-k ton} \end{aligned} \qquad (8)$$

Fig. 5 Conceptual layout of a 1000-MW(e) pressurized-water reactor.

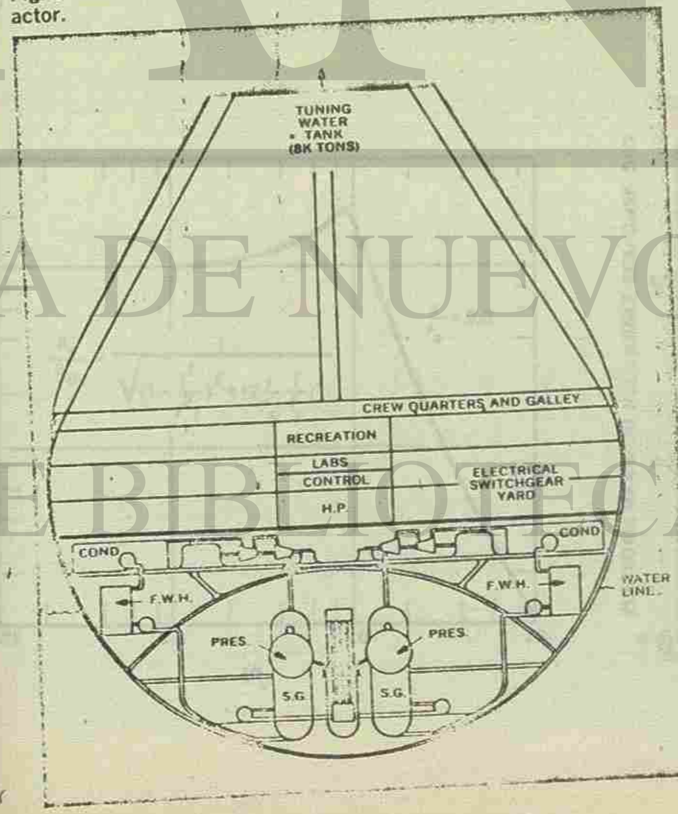


TABLE 2 Pressurized-Water Reactor System

Subsystem	Weight (Millions of Pounds)
Reactor, pressure vessels, and pools	25
Nuclear steam-system equipment	25
Other primary-loop equipment	3
Secondary condenser and feed-water heater	3
Turbine-generator equipment	23
Plant water	24
	103

3 The spherical-platform shell is continuous and ignores the struts to hold the water-ballast tuning tank.

$$\begin{aligned} gI_S &= 2M(150)^2/5 \\ &= 2.97 \times 10^5 \text{ ft}^2\text{-k ton} \end{aligned} \qquad (9)$$

4 The moment of inertia of the water-filled tuning ballast is:

$$\begin{aligned} gI_B &= 8(300)^2 \\ &= 7.2 \times 10^5 \text{ ft}^2\text{-k ton} \end{aligned} \qquad (10)$$

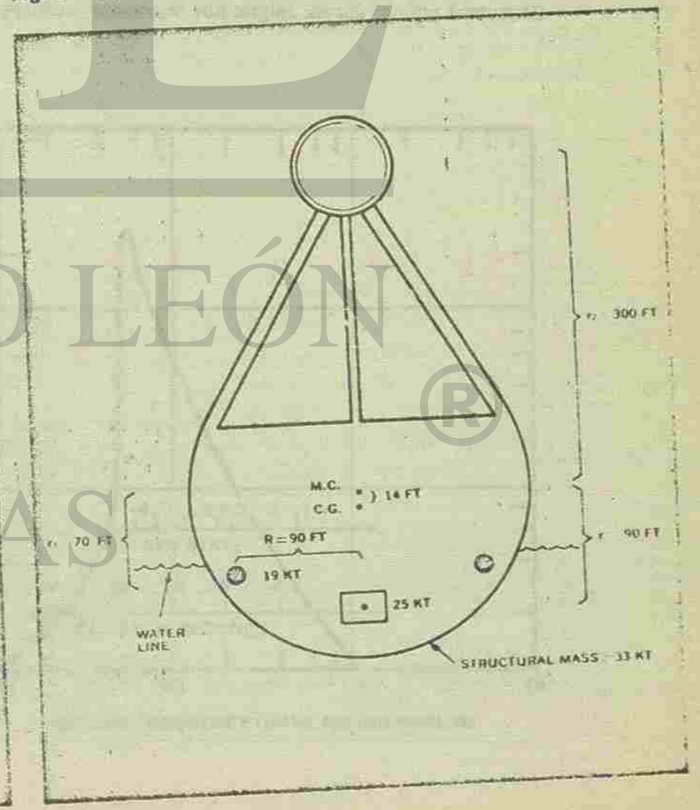
The compound moment of inertia is

$$\begin{aligned} gI_c &= \Sigma gI \\ I_c &= \frac{13.9 \times 10^5}{32} \frac{\text{ft}^2\text{-k ton}}{\text{ft/sec}^2} \\ &= 0.43 \times 10^8 \text{ ft-ton-sec}^2 \end{aligned} \qquad (11)$$

The undamped oscillation of a compound pendulum is described by this equation:

$$I\ddot{\theta} + Wl \sin \theta = 0 \qquad (12)$$

Fig. 6 Approximate mass distribution.



where I is the compound moment of inertia. For small angles of rotation, sin θ equals θ (in radians) so that

$$\ddot{\theta} + \frac{Wl\theta}{I} = 0 \tag{13}$$

Therefore the equation of motion in roll is

$$\ddot{\theta} + \frac{K_r}{I_c}\theta = 0 \tag{14}$$

Integration of this equation between 0 and 2 yields a natural period of oscillation

$$T_r = 2\pi\sqrt{\frac{I_c}{K_r}} \tag{15}$$

and a frequency in roll of

$$f_{nr} = \frac{1}{2\pi}\sqrt{\frac{K_r}{I_c}} \tag{16}$$

As previously noted, $I_c = 0.43 \times 10^8$ ft-ton-sec² and $K_r = 85 \times 10^3 \times 14 = 1.19 \times 10^6$ ft-ton (the weight of the system times the distance between the meta center and the center of mass). Thus the natural period and frequency in roll are

$$T_r = 40.4 \text{ sec} \tag{17}$$

$$f_{nr} = 0.025 \text{ Hz} \tag{18}$$

Consider now the motion of the platform with viscous damping and forced vibration. Previous experimental work has shown that the ratio of viscous damping to critical damping is $r/r_c = 0.3$. The amplification factor (the ratio of the output angular displacement to the input angular forcing function) as a function of the ratio of the forcing frequency f to the natural roll frequency f_r is shown in Fig. 7. The forcing frequency versus angular displacement is obtained from Fig. 4. Using these two figures, one obtains the platform angular roll response versus forcing frequency shown in Fig. 8.

Examination of Fig. 8 leads one to the following conclusions:

1 The maximum roll angle of the platform is 2.8 deg for any possible forcing frequency.

2 Under sea-state-8 conditions, an extremely rare phenomenon, the maximum platform roll would be ~2.0 deg. For such waves to be possible requires a long fetch and deep water. Actually, in nearly all offshore installations, the maximum possible sea state is 6.

3 Under sea-state-6 conditions, the maximum platform roll would not exceed 0.5 deg.

Thus it may be seen that the feasibility of a nonrolling tuned platform as a nuclear-power-plant site can be shown mathematically. Experimental work on small models has demonstrated this expected result.

Reference-Design Heave Response to Sea State

The natural heave frequency F_{nh} of the reference design is computed to be 0.134 Hz. Assuming the ratio of viscous damping to critical damping to be 0.3, Fig. 6 may be applied to establish the amplification factor. The forcing function for vertical displacement is obtained from Fig. 3. Using sea-state-8 conditions, the platform heave responses in vertical displacement as a function of wave frequency are as shown in Fig. 9.

It is significant to note that under sea-state-8 conditions, maximum wave double-amplitude displacement

Fig. 7 Roll amplification versus forcing frequency/natural frequency.

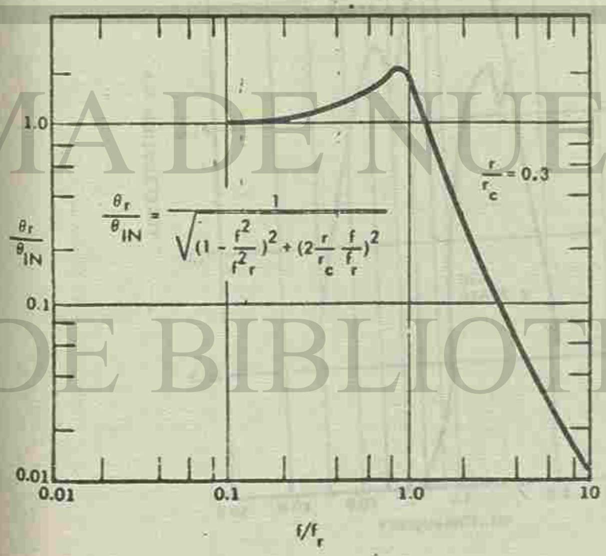
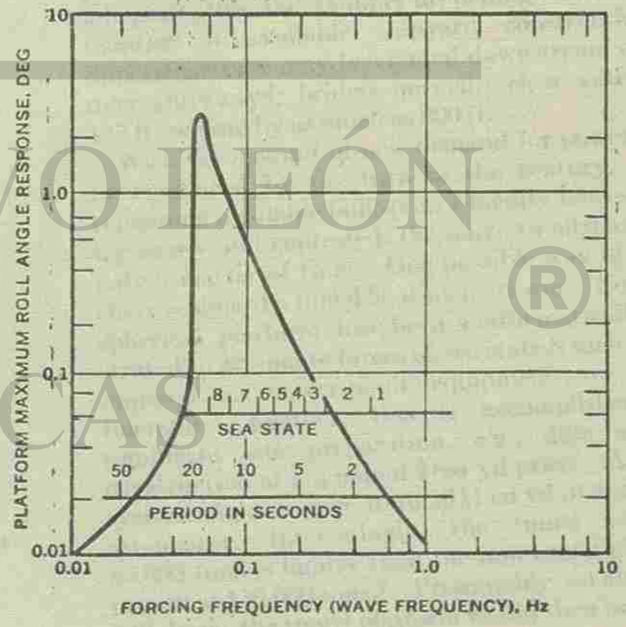


Fig. 8 Platform maximum roll angles versus forcing frequency.



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equals 70 ft; the double amplitude of the platform is 84 ft, or a 7-ft displacement on either side of the static water line.

The major significance of heave response is the g-loads that such motion imparts to the platform and its equipment. The acceleration experienced by the platform is

$$\ddot{a} = -a_0 w^2 \sin wt \tag{19}$$

at maximum acceleration for any forcing frequency $\sin wt = 1$. Thus

$$\ddot{x}_{max} = -a_s w^2 \tag{20}$$

where w equals $2f$, f is the forcing frequency, and a_s is the maximum single amplitude of platform response at the forcing frequency.

Using the curve plotted in Fig. 9, for sea state 8, the maximum accelerations were derived. These data are presented in Fig. 10. It is seen that the maximum acceleration is 0.28 g's at sea state 8 and 0.17 g's at sea state 5, well within design capability of a platform and reactor/turbine-generator equipment.

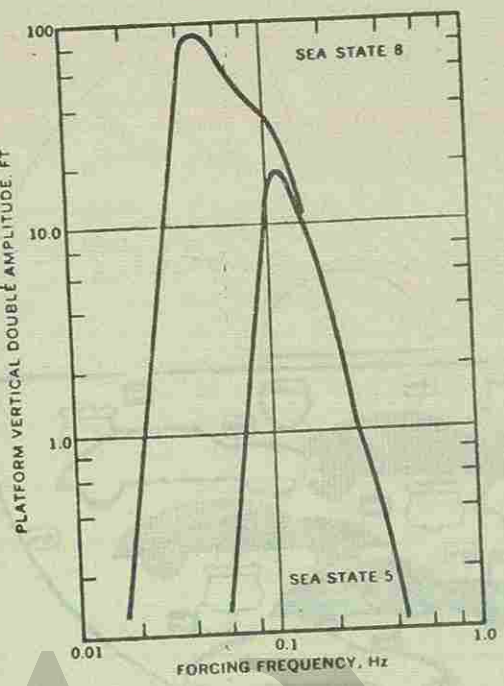

Fig. 9 Platform heave response as a function of sea state.

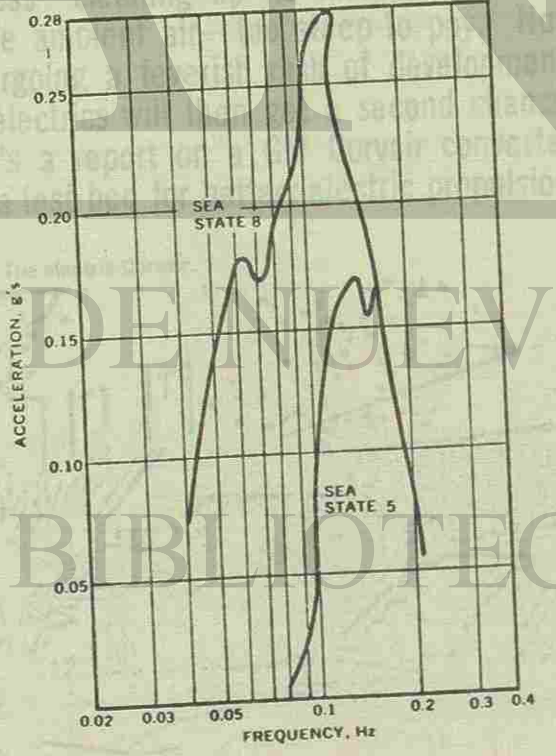

Fig. 10 Maximum acceleration experienced by platform under sea-state-8 conditions.

Conclusions

Problems common to tuned and non-tuned platforms have not been discussed at length herein; they have been examined, however, and viable solutions are evident. These problems include:

1 Mooring: A gimbaled bridle moor which vectors mooring loads through the meta center of a scale-model tuned platform has been tested satisfactorily; vectoring forces through the meta center retains platform tuning.

2 Collision avoidance: Lighted buoys, lighted superstructure, etc.

3 Damage control: Multiple-hull designs, multiple-compartmentation design, energy-absorbing material at and below water line, etc.

4 Construction and towing: Draft can be modified with flotation devices where channel depths are not adequate; this and channel deepening will increase the number of available shipyard construction sites. Superstructures may be erected downstream of bridges over waterways; bridges normally clear waterways by 135 ft, seldom by as much as 200 ft.

With the amount of new demand for power that will be evidenced by the turn of the century, and with remaining available bulk-power-facility land sites growing scarce and contested, the move to offshore siting is only a matter of time. One possible way of going offshore is aboard a tuned floating platform. Such a tuned spherical platform has been mathematically demonstrated to attenuate forces of sea state 8 such that loads imposed on power-plant equipment are eminently tolerable. Further, this is accomplished without significant site preparation, e.g., dike or sea-wall construction at a nominal \$/cu yd price. A non-tuned system might require 10 to 20M cu yd of such sea-force attenuator. Interestingly, the tuned platform at 85,000 tons is lighter than the non-tuned-platform approach at 150,000 tons.[2] Presumably, on an equivalent \$/lb basis, the tuned platform would then be less costly.

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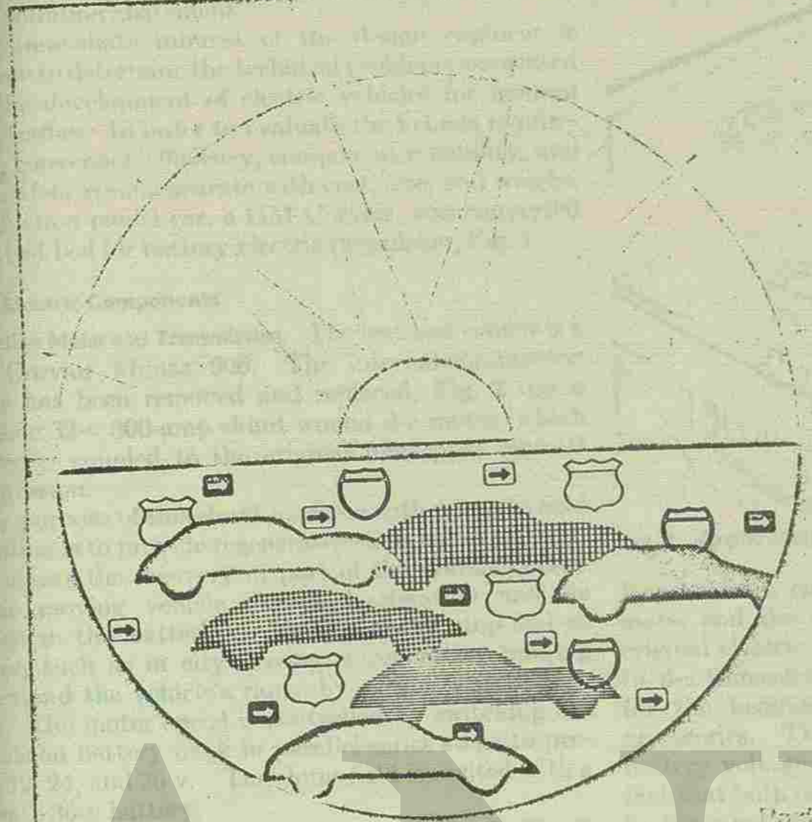
[2] *Aerospace Daily*, May 10, 1971, p. 45.



Part 4—The University of Florida "Electric"

The "electrics" are coming, or will be, if the I-C engine finds the price of its fabulous success—cleaning up its massive pollution of the ambient air—too steep to pay. Now undergoing a feverish rash of development, the electrics will then get a second chance. Here's a report on a GM Corvair converted into a test bed for battery-electric propulsion.

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RECENT developments in high-current-power transistors and silicon-controlled rectifiers combined with a new generation of high-energy electrochemical systems such as the lithium-sulfur battery have brought the

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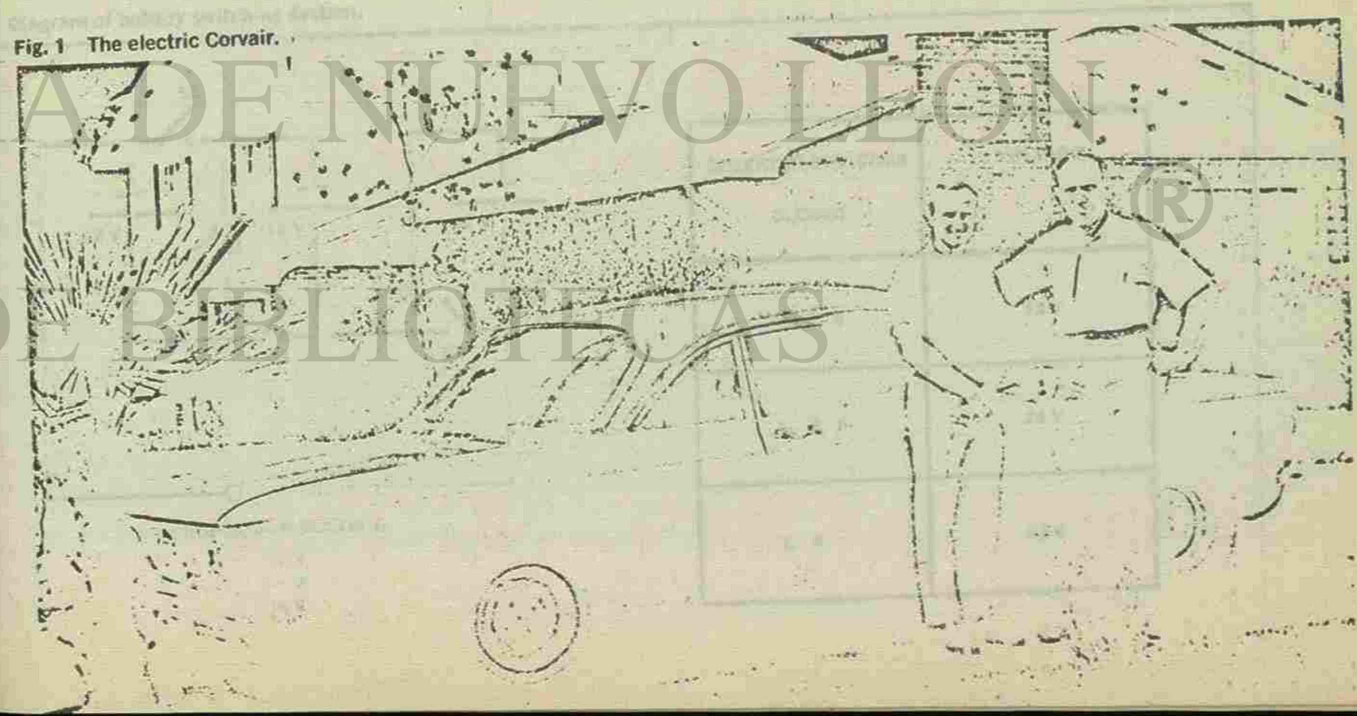
Based on a paper contributed by the ASME Solar Energy Applications Group.

Fig. 1 The electric Corvair.



"electric" into focus again as an effective means to urban pollution abatement.

The immediate interest of the design engineer is therefore to determine the technical problems associated with the development of electric vehicles for modern urban traffic. In order to evaluate the vehicle requirements, conversion efficiency, component reliability, and traffic safety commensurate with cost, size, and weight, a production model car, a GM Corvair, was converted into a test bed for battery-electric propulsion, Fig. 1.

Major Electric Components

Traction Motor and Transmission. The test-bed vehicle is a 1962 Corvair Monza 900. The internal-combustion engine has been removed and replaced, Fig. 2, by a four-pole 32-v 300-amp shunt-wound d-c motor, which is directly coupled to the original four-speed manual transmission.

The purpose of this shunt machine with separate field excitation is to provide regenerative-braking capability. This allows the recovery of part of the kinetic energy of the moving vehicle during deceleration and its storage in the batteries. During heavy stop-and-go service, such as in city driving, regenerative braking can extend the vehicle's range by as much as 25 percent. The motor speed is controlled by switching the propulsion battery bank in parallel-series steps to produce 12, 24, and 36 v. The shunt field is excited with a separate 36-v battery.

Battery System. There are two battery systems, Fig. 3, used in the electric Corvair, namely: a switchable-voltage propulsion battery and a smaller fixed-voltage field-excitation battery which also furnishes the power for the control circuits. Both batteries are of the vented nickel–cadmium type.

Propulsion Battery. The traction battery consists of three banks, 12 v each. Every bank contains 20 cells in series-parallel, thus a total of 60 cells are used. The maximum battery voltage is 36 v at 80-amp-hr capacity.

Field-excitation Battery. The field-excitation system consists of a 36-v 24-amp-hr-capacity Ni–Cd battery bank.

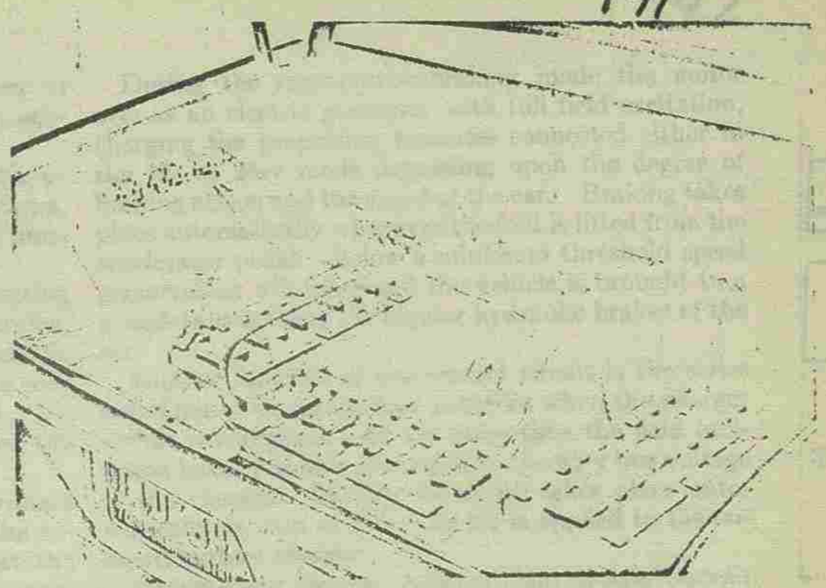


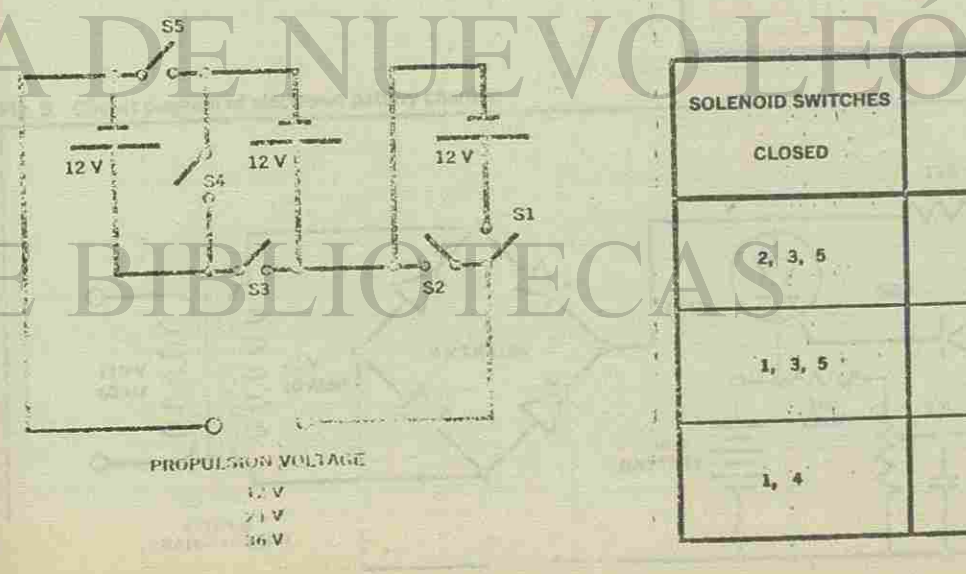
Fig. 2 Engine compartment.

It provides a constant field current to the propulsion motor and also powers all the control circuits and the original electric system of the car by the use of a d-c–to–d-c transistor power converter to generate the 12 v for the headlights, wipers, horn, radio, and other accessories. The advantage of matching the field-battery voltage with the propulsion battery lies in the fact that both can be charged simultaneously in parallel by the same constant-voltage battery charger, Fig. 3.

Charger. Proper voltage regulation of the charger potential is important to the cell life of the battery. Too high a voltage will lead to excessive hydrogen generation, profuse gassing, spewing of electrolyte, overheating, and eventual thermal runaway, resulting ultimately in irreversible damage to the battery. Too low a voltage will cause cell imbalance requiring capacity reconditioning.

The optimum cell voltage under charge is 1.5 v at 75 F. Thus for the 36-v Corvair battery the charger voltage is maintained at 45 v electronically, Fig. 4, by means of a Zener reference diode and silicon-controlled

Fig. 3 Diagram of battery switching system.



SOLENOID SWITCHES CLOSED	VOLTAGE
2, 3, 5	12 V
1, 3, 5	24 V
1, 4	36 V

rectifiers, Fig. 5. The charger has been designed to furnish 30 amp, yielding 1350 w of power to the batteries.

Control Circuit. The purpose of the control circuit is to provide three different traction-motor drive voltages, 12, 24, and 36 v, which in combination with the four-speed transmission will provide 12 steps in speed.

This is obtained by six power solenoids connecting the propulsion-battery sections alternately in parallel, series-parallel, and all in series. First, two banks in parallel provide 12 v. Then an additional bank is connected in series with the first two still in parallel. Finally, all banks are in series, providing 36 v for the motor amature.

The power solenoids are activated by microswitches operated by a cam plate, Fig. 6, connected to the accelerator linkage. Diode OR gates insure that the correct solenoids are energized in proper sequence without shorting out the individual battery banks, Fig. 7.

The field-excitation voltage is constant at all times. The excitation current can, however, be reversed, which in turn will change the direction of motor rotation, shifting the vehicle electrically into reverse drive.

During the regenerative-braking mode the motor acts as an electric generator with full field excitation, charging the propulsion batteries connected either in the 12- or 24-v mode depending upon the degree of braking action and the speed of the car. Braking takes place automatically whenever the foot is lifted from the accelerator pedal. Below a minimum threshold speed regeneration will cease and the vehicle is brought to a complete stop using the regular hydraulic brakes of the car.

Another function of the control circuit is the series switching of the propulsion batteries when the charger circuit is energized. At the same time the field excitation battery is also connected to the 45-v bus voltage of the charger. Battery switching takes place automatically as soon as 110 v, 60 Hz is applied to the on-board battery charger.

Charging-Power Sources. Although the electric Corvair is at present usually recharged from 110-v 60-Hz power, provisions have been made to accommodate alternate power sources such as solar energy.

Concurrent with the development of our test-bed vehicle, research and development is carried out in our Solar Energy Laboratory at the University of Florida.

Fig. 4 Charge voltage versus cell temperature.

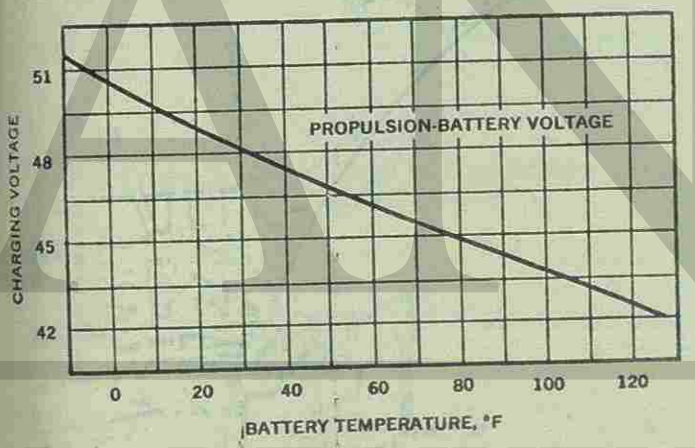
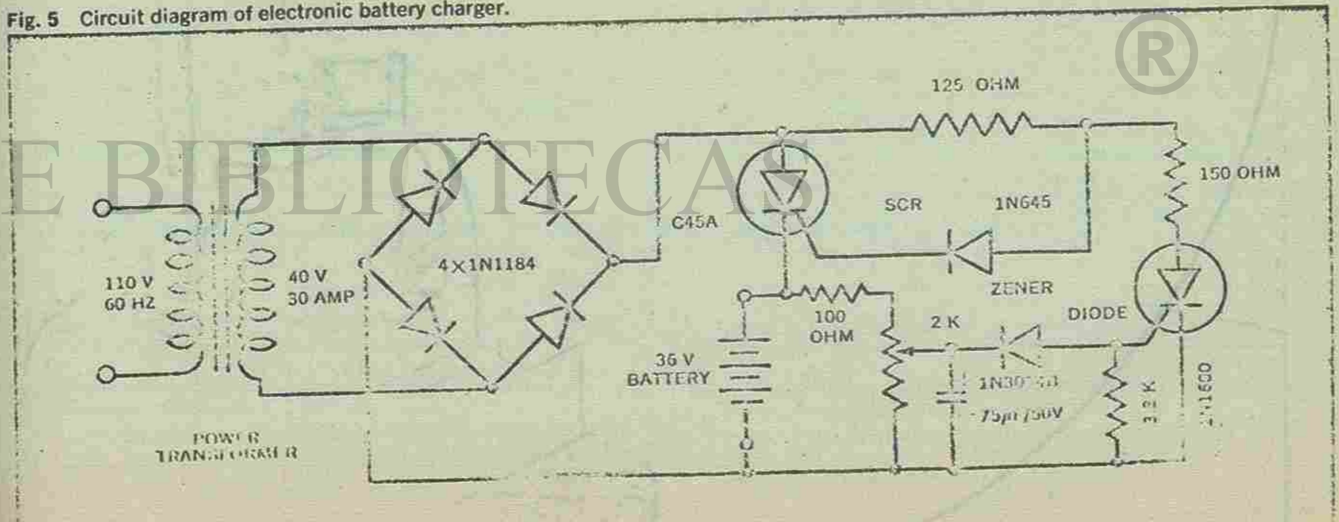


Fig. 6 Cam plate.

Fig. 5 Circuit diagram of electronic battery charger.



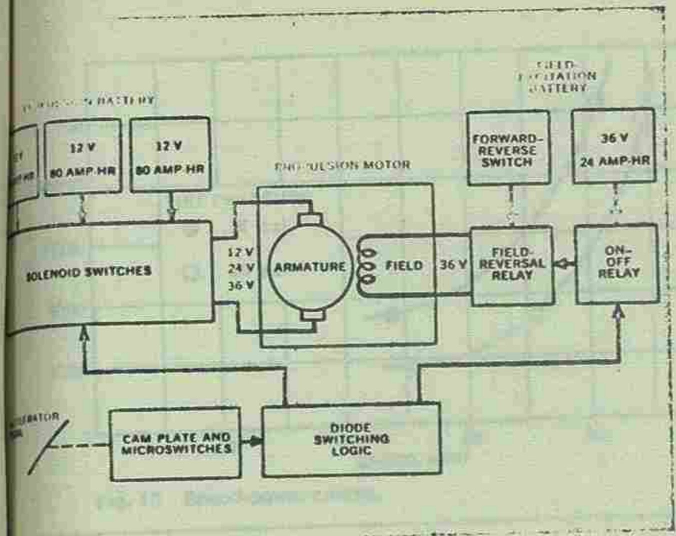


Fig. 7 Diagram of control circuit.

Emphasis has been placed on the Stirling-cycle solar engines coupled to d-c generators to recharge the Corvair. Fig. 8 shows a $\frac{1}{3}$-hp hot-air engine with a 5-ft solar collector and a d-c generator. Fig. 9 presents

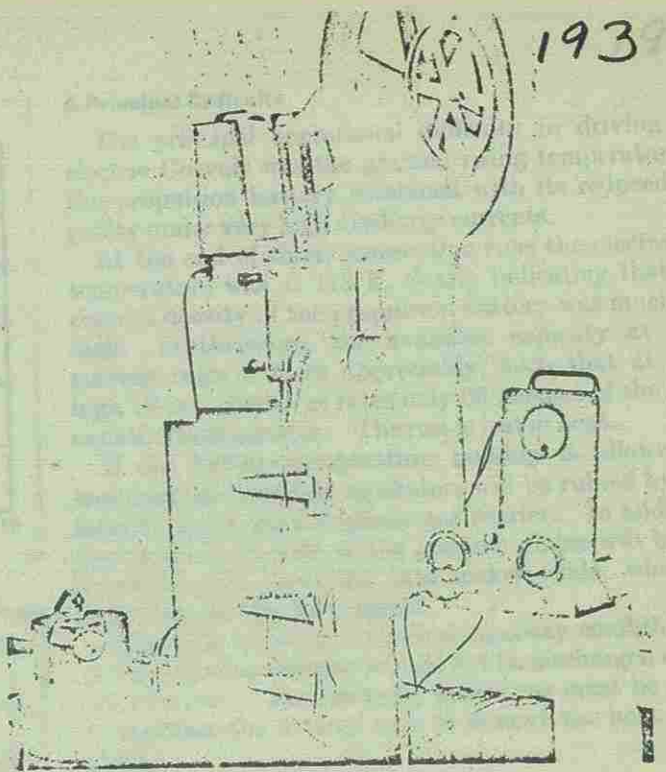
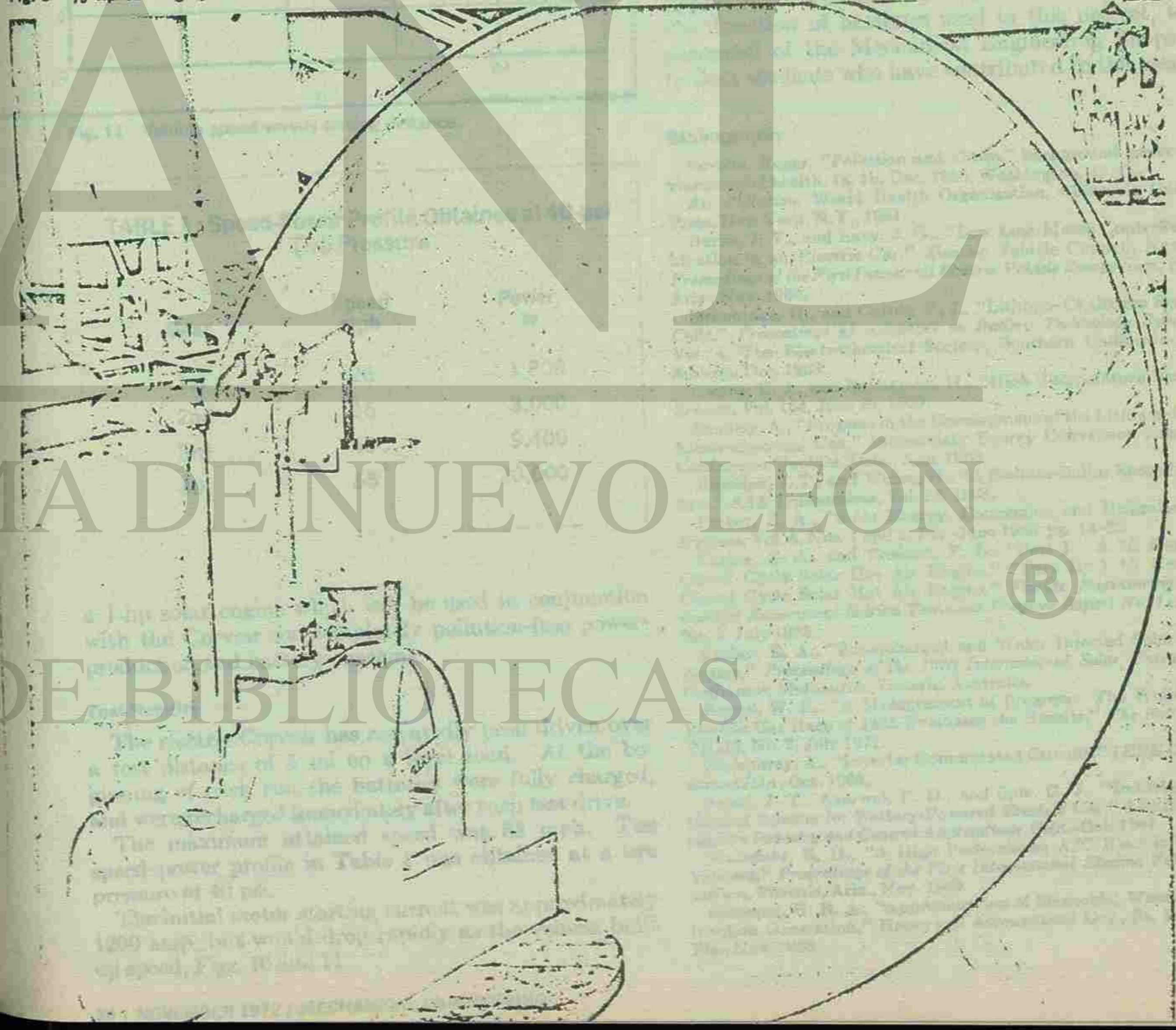


Fig. 9 1-hp solar engine on test stand.

Fig. 8 ⅓-hp Stirling-cycle solar engine.



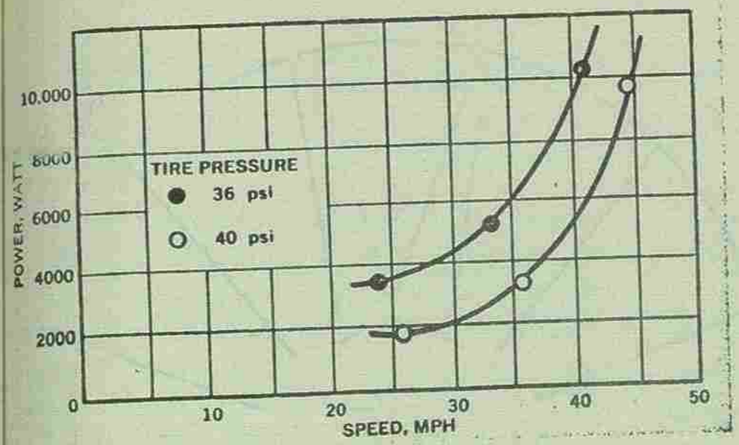


Fig. 10 Speed-power curves.

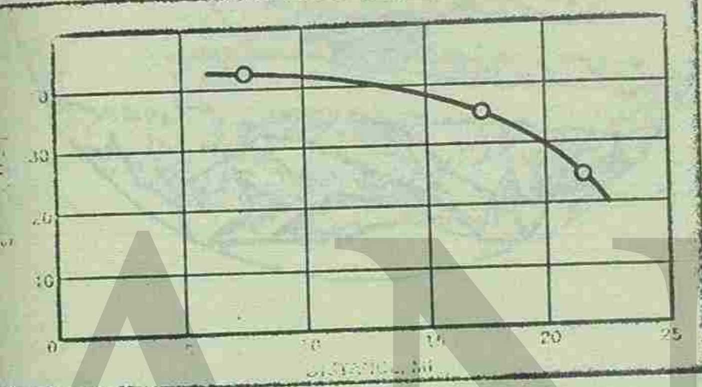


Fig. 11 Vehicle speed versus driving distance.

TABLE 1 Speed-Power Profile Obtained at 40-psi Tire Pressure

Gear	Speed mph	Power, w
1st	26	1,800
2nd	36	3,000
3rd	45	9,400
4th	55	20,000

a 1-hp solar engine which will be used in conjunction with the Corvair for completely pollution-free power-production and battery-charging.

Test Results

The electric Corvair has repeatedly been driven over a test distance of 4 mi on a level road. At the beginning of each run the batteries were fully charged, and were recharged immediately after each test drive.

The maximum attained speed was 58 mph. The speed-power profile in Table 1 was obtained at a tire pressure of 40 psi.

The initial motor starting current was approximately 1200 amp, but would drop rapidly as the vehicle built up speed, Figs. 10 and 11.

A Principal Difficulty

The principal operational difficulty in driving the electric Corvair was the gradual rising temperature of the propulsion battery combined with its reduced capacity under very high discharge currents.

At the end of three consecutive runs the electrolyte temperature was at 178 F, clearly indicating that the current density of the propulsion battery was much too high. Furthermore, the available capacity at high current rates reduces appreciably, such that at very high 10-min discharge rates only 65 percent of the total capacity is attainable. The rest is lost in heat.

If the battery-temperature buildup is allowed to continue the electrode separators will be ruined by disintegration of the cellophane gas barrier. In addition, the nickel hydroxide of the positive plates will be dehydrated and converted into nickel oxide, which is electrochemically irreversible.

Therefore, because of thermal runaway conditions, a nickel-cadmium battery should not be discharged above the 1-hr rate. Furthermore, provisions must be made to ventilate the battery cells to remove the heat effectively.

Acknowledgments

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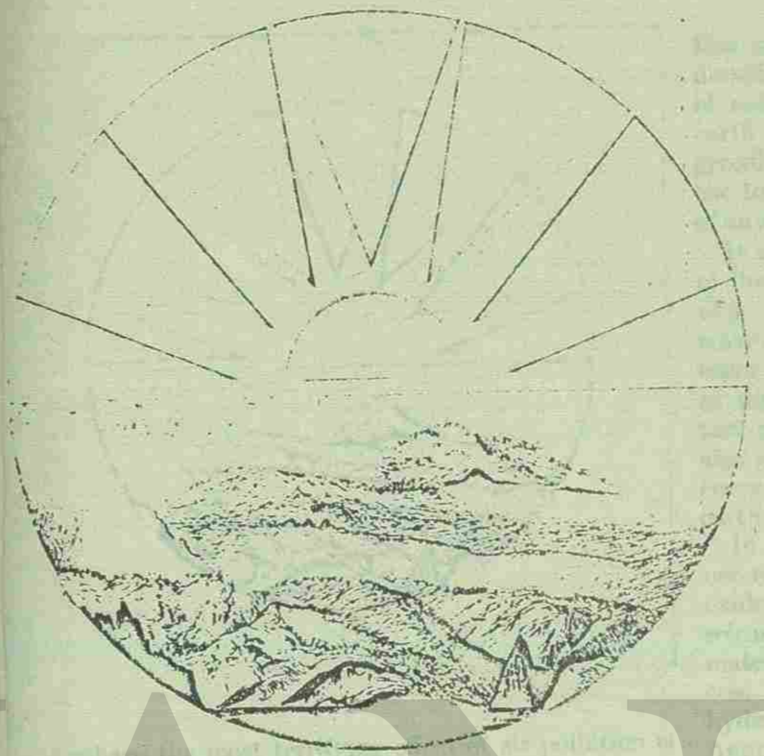

THE SOLAR ERA

Part 5—The Pollution of Our Solar Energy

Extreme consequences of air pollution could be: another ice age, melting polar ice caps, massive carcinogenic UV radiation. Government, industry, and the public must make the effort and pay the price to reverse the rising pollution down to a rational minimum.

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MAN HAS lived on the earth for many thousands of years and has proved to be a very successful species. He has proliferated throughout the planet, subjugated other species to his own use, and released on the earth new man-made processes which match the intensity and scope of natural ones. Now man finds reason to question his success, because the very power that he has exerted on the rest of nature threatens his own survival.

Urbanization and industrialization are two of the most significant and dynamic phenomena of the twentieth century. Their consequences, both good and bad, are being experienced throughout society. More and more man is beginning to take a hard if somewhat bleary-eyed look at the urbanized environment in which he lives. Frequently his buildings are covered with grime, his rivers darkened and turgid with wastes, and his air thickened with strange corrosive particles.

Pollution is a predictable result of the tendency of humans to congregate. Man has continually polluted one of his basic needs—the atmosphere. Two major contributions to air pollution are from the smokestacks of industry and the exhaust pipes of automobiles.

The public usually considers the aesthetic, economic, and health effects of air pollution. The presence of smoke and smog dims the sun and sky, which offends the aesthetic sense. Injury to vegetation and livestock, corrosion and soiling of materials and structures, and depression of property values are examples of economic damage caused by air pollution. A more significant effect, though, is the effect upon human health. Circumstantial evidence suggests that air pollution is a contributory cause of the high cancer rate found in urban areas. Rasping coughs, smarting eyes, nausea, and irritability are among the lesser symptoms attributed to air pollution.

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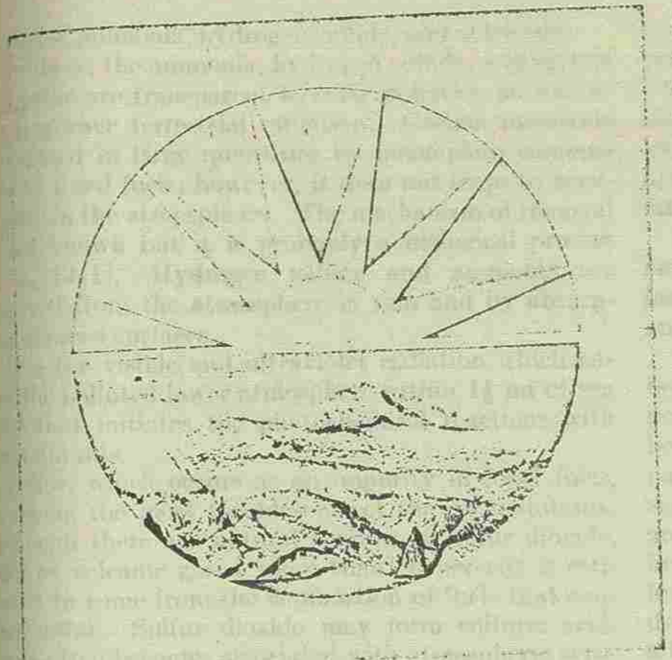
Based on a paper contributed by the ASME Solar Energy Applications Group.



Perhaps the most terrifying effect of air pollution is never mentioned. What if the concentration of air pollution were to become so dense that the temperature of the earth was affected? Greater reflection of the incoming solar radiation could lead to another ice age. If carbon dioxide were carelessly allowed to build up in the atmosphere and absorb the long-wave terrestrial radiation, the consequence might be a temperature rise capable of melting the polar ice caps.

Chemical reactions are known that can remove the ozone in the upper atmosphere, and this process, if carried far enough, could result in most living things being roasted to death as more ultraviolet radiation reached the earth.

These examples are extremes which we hope will never happen, but they could well become reality if man continues to pollute the solar radiation. In all likelihood, air pollution can never be entirely eliminated, but it can and must be reduced from its present levels. The question is whether governmental institutions, industry, and the public are willing to make the effort and pay the price.

Effects of Solar Radiation

As solar radiation falls on the earth approximately 35 percent is screened out by the atmosphere in reflection or scattering back into space. Owing to the very strong absorption by O_2, N_2, O, N, and O_3 up to 3000 angstroms, the solar spectrum is very sharply terminated. The rest of the solar radiation is absorbed and used in heating the lower atmosphere, maintaining the earth temperature, and providing the energy for some atmospheric and biological processes. As the earth is in steady state with respect to space, it reradiates all this energy throughout a broad range of wavelengths with a flat maximum at 12 microns [1].[4] In this range of the spectrum, water vapor and carbon dioxide in the atmosphere absorb significant amounts of radiation, forming a roof above the surface of the earth which functions as does the roof of glass over a greenhouse. As a result, the earth is protected from the terrible extremes of heat and cold that the surface of an airless planet experiences.

It is solar energy which provides the driving energy of the water cycle: evaporating the water, lifting the vapor in clouds, then depositing it as rain or snow from where it will flow back to be evaporated again. Another contribution of solar energy is in the generation of winds that are an important part of the temperature-regulating system of the earth. Solar energy is also stored in the very high atmosphere as electrical energy which daily varies the magnetic field of the earth.

In the process of photosynthesis [1, p. 64] plants use radiant energy from the sun to convert carbon dioxide and water into carbohydrates, at the same time releasing oxygen into the atmosphere. When plant materials decompose or are eaten by animals, the process is reversed. Oxygen is used to convert carbohydrates into energy plus carbon dioxide and water. Annually, about 110 billion tons of carbon dioxide are evolved in photosynthesis. This is roughly 5 percent of the carbon dioxide in the atmosphere. Under normal conditions the amounts of carbon dioxide and oxygen in the atmosphere remain approximately in equilibrium from year to year. The actual amount of solar energy diverted into living systems is small in relation to the earth's total energy budget. Only about one-tenth of 1 percent of the energy received from the sun by the earth is fixed in photosynthesis. The production of fossil fuels also is based on the carbon cycle.

In the atmosphere one major photochemical reaction occurs: High-energy radiation from the sun reacts with oxygen. At heights above 50 mi oxygen exists almost exclusively in the monatomic form. Dropping to lower levels the conditions become favorable for the formation of triatomic oxygen or ozone [2]. The region of greatest ozone concentration is reported to be between 10 and 20 mi. The principal molecular air constituents—carbon dioxide, nitrogen, oxygen, and water—are all transparent to the visible and ultraviolet radiation down to at least 2000 Å. The ozone layer is a filter for this ultraviolet radiation, which, if not stopped, could ruin all vegetable and animal life.

As a matter of fact solar radiation has dictated the actions and habits of life on earth, since it provides the light by which we see and by means of photosynthesis the food we eat and the oxygen we breathe. Besides, sunshine has many beneficial effects for the health; one of the best known is the production of vitamin D which is essential for the absorption and metabolism of calcium.

Atmospheric Pollutants

The major air pollutants, most resulting from the combustion of fossil fuels, are carbon monoxide, sulfur and its oxides, nitrogen oxides, hydrocarbons and solid

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[4] Numbers in brackets designate References at end of article.

particles, ammonia, hydrogen sulfide, and aldehydes.

Of these, the ammonia, hydrogen sulfide, and carbon monoxide are transparent to solar radiation as well as to long-wave terrestrial radiation. Carbon monoxide is emitted in large quantities by incomplete combustion of fossil fuels; however, it does not seem to accumulate in the atmosphere. The mechanism of removal is not known but it is probably a biological process [2, p. 1341]. Hydrogen sulfide and ammonia are removed from the atmosphere in rain and by absorption at moist surfaces.

It is the visible and ultraviolet radiation which enters the polluted lower atmosphere within 1½ mi of sea level that initiates the photochemical reactions with air pollutants.

Sulfur, which occurs as an impurity in fossil fuels, is among the most troublesome of the air pollutants. Although there are natural sources of sulfur dioxide, such as volcanic gases, more than 80 percent is estimated to come from the combustion of fuels that contain sulfur. Sulfur dioxide may form sulfuric acid, which often becomes associated with atmospheric aerosols, or it may react further to form ammonium sulfate. A typical lifetime in the atmosphere is one week [3]. Sulfur exhibits moderate absorption in the ultraviolet end of the spectral range. This radiation does not represent sufficient energy to disrupt a bond in the molecule, and it must be assumed that initially only activated molecules are created. These energized molecules may either revert to their original state, dissipating the absorbed energy, or they may react with surrounding molecules. In the atmosphere, where oxygen concentration is higher in comparison to sulfur dioxide, ozone and sulfur trioxide are the products. It is possible, however, that sulfur compounds are accumulating in a layer of sulfate particles in the stratosphere. The mechanism of formation, its effects, and its relation to man-made emissions are not clear. These fine particles could have an effect on radiation from the upper atmosphere, thereby affecting mean global temperatures [4].

Nitrogen oxides occur naturally in the atmosphere as nitrous oxide, NO, and nitrogen dioxide, NO_2. The production of nitrogen oxides in combustion is highly sensitive to temperature. It is particularly likely to result from the explosive intermittent combustion taking place in the internal-combustion engine. Nitrous oxide is the most plentiful at 0.25 ppm and is relatively inert. Nitrogen dioxide is a strong absorber of ultraviolet radiation and triggers off photochemical reactions that produce smog [3]. Therefore, in the atmosphere, where the oxygen–nitrogen dioxide ratio is very large, ozone is produced.

Another, perhaps minor, source of ozone formation by photochemical reactions is from aldehydes which are produced in vast quantities as industrial and domestic wastes, and from incomplete combustion in automobile engines, incinerators, etc. [5].

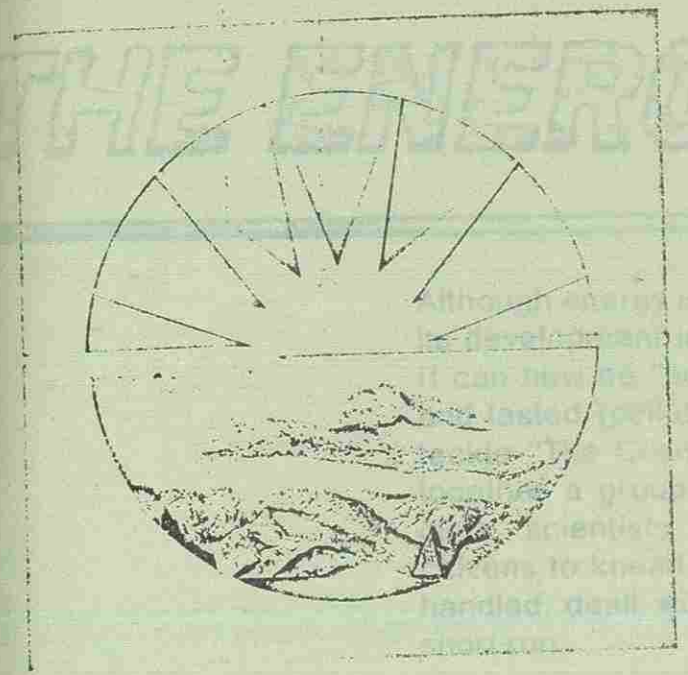
Hydrocarbons are emitted naturally into the atmosphere from forests and vegetation and in the form of methane from the bacterial decomposition of organic matter. Human activities account for only about 15 percent of the emissions, but these contributions are concentrated in urban areas. The reactions of hydrocarbons with nitrogen oxides in the presence of ultraviolet radiation produce the photochemical smog that appears so often over Los Angeles, Detroit, and other cities [3].

All these reactions are minor in their effect on the amount of solar radiation incident on the earth's surface, but they are associated with high air temperatures and reduced intensity of ultraviolet radiation [6].

Fine particles, carbon dioxide, and water vapor will be introduced into the stratosphere by supersonic transport, and the stratosphere is the region which it would be the most dangerous to pollute. A doubling of fine particles and a 10 percent increase in water vapor could significantly raise the temperature of the stratosphere and increase cloudiness. More solar radiation would be reflected back into space with the overall effect of lowering the earth's mean temperature. It has been determined that atmospheric temperature rose generally between 1860 and 1940. Between 1940 and 1960, although slight warming occurred in the northern part of Europe and in North America, there was a slight lowering of temperature for the world as a whole. The average annual temperature dropped one-half a degree.

There is also the possibility that newly introduced stratospheric pollutants may affect the concentration of ozone in this region. The likelihood of this happening is very slight, but if a decrease in ozone were initiated by some chemical reaction, more high-energy ultraviolet radiation would be able to reach the earth's surface. If this were to happen, people would experience burns caused by radiant energy many times greater than the radiation that causes sunburn on the clearest, hottest summer day.

Perhaps the most serious air pollution problem is the increase of carbon dioxide which is being added to the atmosphere. The injection of large quantities of carbon dioxide into the atmosphere in the past few decades has been extremely sudden in relation to important natural time scales. If the oceans were perfectly mixed at all times, carbon dioxide added to the atmosphere would distribute itself about five-sixths in the water and one-sixth in the air. In actuality the distribution is about equal. Since 1860 the concentration of carbon dioxide in the atmosphere has increased from 290 ppm to about 320 ppm. There is a possibility that this increase will lead to a worldwide rise in temperature. Carbon dioxide has strong absorption bands, particularly in the infrared region where most of the thermal energy radiating from the earth is concentrated at wavelengths of from 12 to 18 microns. Syukuro Manabe and R. T. Wetherald calculated that a rise in atmospheric carbon dioxide from 320 to 600 ppm would increase the average surface temperature by 4.25 deg assuming average cloudiness, and 5.25 deg assuming no clouds [3, p. 183]. This increase would cause the polar ice caps and glaciers to melt, raising the level of the sea and submerging great coastal cities such as New York and Vancouver.



Health and Other Consequences

Observations conducted in Tokyo demonstrated that ultraviolet radiation was significantly decreased by city smog [7]. The radiation was measured in the center of the city and in the suburbs. It was found that the intensity of the total radiation recorded in the center of the city was 70 or 80 percent of that recorded in the suburbs. However, the center only received 40 to 50 percent of the ultraviolet radiation that the suburbs received. It can be concluded that the attenuation of the total and of the ultraviolet radiation is an important problem for city inhabitants. Ultraviolet radiation produces a stimulus which allows the epidermis layer of skin of the human to make vitamin D. It has been proved that vitamin D prevents the disease known as rickets. The biological effects of several of the products of the reactions, including ozone and complex organic molecules, are often injurious. Ozone has highly detrimental effects on vegetation, but so far they have been localized. No worldwide effects have been discovered as yet [8].

Although it is improbable and not expected to happen in the future, the ozone absorption band could shift, due to air pollutants, with the result that ultraviolet radiation with wavelengths shorter than 2900 Å could penetrate the atmosphere. The predictable consequences on human health would be an increase in the rate of skin cancer and the generation of highly dangerous malignant melanomes which arise from the pigment cells. Even the little ultraviolet radiation which is not presently absorbed by the atmosphere can cause severe sunburn.

In the last 200 years, the industrialized nations have used two-fifths of the world's present supply of coal. At that rate, there will be no coal reserves by the twenty-third century. However much these periods may be stretched by unforeseen discoveries and improved technology, the end of the fossil-fuel era will inevitably come [8, p. 186]. Man will have to find another form of energy, possibly direct harnessing of solar radiation [9], [3, p. 178]. But what if at the same time he is polluting it?

Polluted air also means less sunlight. Cities today average from 15 to 20 percent less sunshine annually than the surrounding countryside. However, the consequences of such a loss, as far as human life is concerned, cannot yet be clearly seen.

On the other hand, a worldwide increase in cloudiness will certainly have important repercussions on the growth of plants and crops, and perhaps too, by way of a reduction in photosynthesis, on animal and human life.

Conclusion

It is possible that if the present intensity of atmospheric pollution were to continue for several centuries man would disturb the harmony of this planet and degenerate its climates, vegetation, and life. However, this prediction cannot really be based on observations made to date.

Some atmospheric pollutants, such as carbon monoxide, water vapor, and solid particles, could affect the amount of solar radiation reaching the earth, but it is not clear whether it would be more scattering back into space or more absorption, or whether the consequence would be a decrease or an increase in the mean temperature of the earth.

Other pollutants such as nitrogen oxides and sulfur oxides would alter the quality rather than the quantity of solar radiation by initiating processes capable of removing ozone from, or adding it to, the atmosphere, thus changing the present natural filter to ultraviolet radiation.

Whichever assumption may be right, we do not want to experience the ultimate test. This underlines the drastic lack of accurate worldwide and long-term solar-radiation measurement, without which no hypothesis concerning the future and the security of our environment can be formulated. It would be a shame if our solar energy were badly polluted by the time our fossil fuels run out.

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THE ENERGY CRISIS

Although energy is not a "thing," it has assumed, through its development into a crisis, the attributes of a "thing." It can now be "seen" (brownouts and blackouts), smelt and tasted (pollution), and felt (in the pocketbook). To tackle "The Crisis," the Winter Annual Meeting brought together a group of nationally known engineers, financiers, scientists, government officials, and concerned citizens to knead the problem into a shape that could be handled, dealt with, and perhaps solved, at least for the short run.

Defining the Crisis

A Scientist's View. David C. White, Ford Professor of Engineering, Massachusetts Institute of Technology: The nation's widely publicized "energy crisis" is usually expressed in terms of two major concurrent symptoms: first, the enormous volumes of energy consumed at an exponential growth rate, generating pollutants that affect mankind and the total biosphere in unknown and possibly injurious ways, unpredictable over the long term with today's knowledge; second, the concurrent depletion of our domestically most desirable and easily obtainable fossil fuels. Absolute resources are not today at issue, since for all fuels only a small fraction of the total resources in place have been drawn upon to supply our total energy consumption from antiquity to the present.

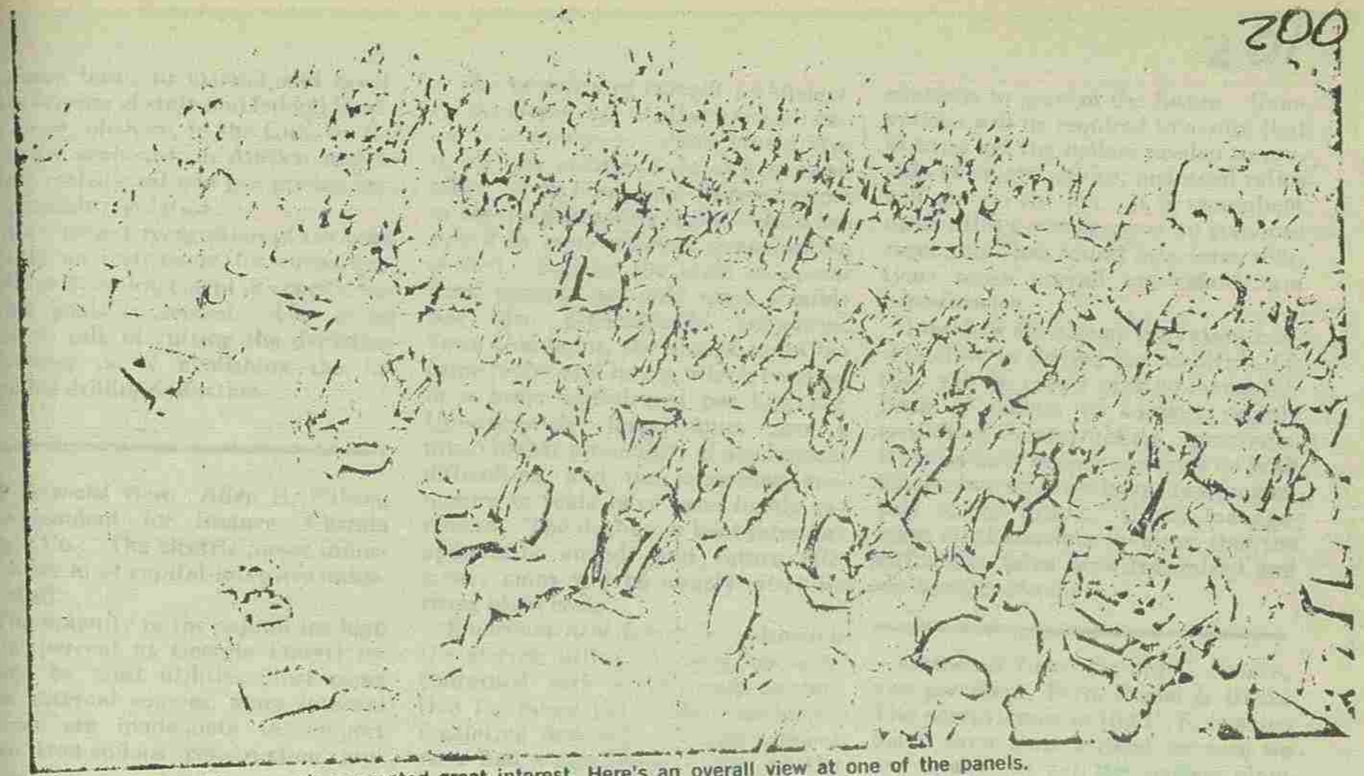
A continuing exponential growth in energy consumption anywhere near the average historic growth rate (approximately a 20-year doubling time) superimposed upon the present magnitude of consumption may run into a domestic-resource limitation of economically obtainable fossil fuels. At today's increasing rate of consumption, another century of low-cost domestic fossil fuels may not exist. Other fuels, particularly nuclear fuels in immense quantities, are domestically available if technology develops fusion or resolves the safety and waste-management problems of fission processes. Depletion of economically producible and environmentally acceptable fossil-fuel resources, increasing daily environmental disturbances, and possible long-term disruption of the total ecosphere are highly probable consequences of our energy-consumption practices.

The above factors, however, are symptoms or effects. To understand why these effects are occurring, we must review the factors influencing energy, environment, and economic interactions. They distill to the following conclusion:

The time response of the marketplace to economic stimulation is much shorter (at least an order of magnitude) than the time response to stimulation of research and development in physical science, technology, biology, or ecology. Decisions based on cost-benefit analysis at current interest rates yield conclusions valid for profit-making industries but not for society. Major revision in institutional factors to allow proper economic interactions between the marketplace and research and development and institutional changes, with their vastly different dynamic-response characteristics, is a first requirement for dealing with the energy crisis. The energy crisis is usually defined in terms of symptoms, not causes. Today's problems are the result of poor foresight and of poor decisions made decades ago. Unless today's approaches can look decades ahead and at the same time deal with today's problems, the energy crisis, no matter how defined, will continue, and its consequences will increase in severity.

A Utility View. W. Donham Crawford, president, Edison Electric Institute: Last year the electric utility industry used slightly more than 328 million tons of coal, 396 million bbl of oil, 3993 trillion cu ft of gas, and 900 tons of uranium. These fuels were used to generate 1532 million megawatt-hours of electricity. During the next two decades, our use of electric energy can be expected to about quadruple, and in the absence of a presently unforeseen technological breakthrough, vastly increased quantities of

Based on The Energy Crisis Forum held concurrently with the ASME Winter Annual Meeting, Nov. 26–30, 1972, New York, N. Y. (A general report of the Winter Annual Meeting can be found in the "ASME News.")



"The Energy Crisis" symposia generated great interest. Here's an overall view at one of the panels.

the basic fuels—particularly coal and uranium—will be required to generate it.

Most energy forecasters agree that by the end of this century about half the energy consumed in this country will be used to generate electricity. To make this possible, the electric utility industry must add substantial amounts of new generating capacity and continue to extend and expand transmission without adversely affecting the reliability of customer service or environmental quality. There have been delays in doing this; the biggest are associated with construction problems.

Intervenors also play a role. The objections we hear most frequently are that electricity contributes to our environmental damage—a position which is generally based on incomplete information and which ignores the contribution electricity makes to cleaning up the environment. We hear that electricity uses too much of our fuel resources—a position that overlooks the fact that where electricity is not used, raw fuels are likely to be consumed directly. We hear that electricity is too cheap—a position with which many utility companies are forced to agree. We hear that the U. S. uses too much electricity, and that consumption should be discouraged by arbitrarily adjusting prices to penalize increased use.

We agree that we must use energy more efficiently. In some cases, achieving the goal of using less total energy will mean the use of more electricity. Substitution of electrified mass transit for automobiles and diesel-powered buses is a good example.

A few guidelines for the future in relation to energy are in order:

We should use energy wisely, not waste it. This means giving greater attention to insulation. It means putting windows back in buildings so that we can ventilate them naturally under some weather conditions. It probably means using smaller cars and more mass transit. Overall, it means looking at each energy use and being conscious of its efficiency and appropriateness.

Research and development efforts should be expanded in order to overcome the technological problems facing the industry and to open up new energy resources. The R&D program should be financed voluntarily and administered by industry, not by government.

Improved regulatory procedures need to be developed. The Atomic Energy Commission, state licensing agencies, and all the other parts of our complex regulatory process need to think about streamlining and, where possible, consolidating their activities.

Probably most urgent, there is a need to establish a national energy council based on the pattern of the National Security Council. A national energy council, composed of the heads of the principal agencies with significant energy responsibilities and reporting directly to the president, could be an effective coordinator of our wide-ranging energy policies.

The Government View. Rush Moody, Jr., commissioner, Federal Power Commission: No one person can state "the government view," for there is no "government view" in the sense of one data base, one delineation of cause and effect, one measurement of probable impact, one program, one agreed-upon set of solutions.

Is the energy crisis real? The answer is yes! How do we know there's a crisis? For four years running we have been consuming gas twice as fast as we are finding new reserves. Where we had a reserve-life index of roughly 20 years in the early 1960s, we were down to 11 years at the end of 1971. Seven interstate pipelines could not deliver the volumes of gas they had contracted to deliver last winter. The shortfall was approximately 500 billion cu ft of gas; this required curtailments which resulted in lower-than-contracted-for deliveries to many customers. Reports filed with us for this winter heating season foretell a doubling in the number of pipelines which have run short—from seven to 15—and a doubling of the shortage—from 500 billion to 1 trillion cu ft of gas.

Where did the crisis come from? In simplest terms, we didn't pay our way as we went. The opportunity cost of natural gas was ignored as the regulatory posture became one based on historic costs. The result was to keep the wellhead price low, but a corollary result was to forfeit replacement of supplies. Markets grew rapidly in response to this illusory "bargain" price of gas, and so, as the result of high demand and low price, we are faced with real concern for the adequacy and reliability of future service, as well as with frustration at higher prices which appear inevitable—for supplements or for underutilized facilities.

What do we do now? We need to insure development of our domestic-resource base; to expand and accelerate leasing of state and federal lands, on shore, offshore, in the Gulf, on the Atlantic seaboard, in Alaska; and to effect realistic oil and gas pricing and responsible regulation.

Also, honest recognition of tax policies as an instrument for encouragement or discouragement of specific national goals is needed. This is no time to talk of cutting the depletion allowance or of abolishing the intangible drilling deduction.

A Financial View. Allen B. Wilson, vice-president for finance, Georgia Power Co.: The electric power industry is the most capital-intensive industry of all.

The majority of the capital (as high as 80 percent at Georgia Power) required by most utilities must come from external sources, since internal sources are inadequate to support these tremendous construction programs.

There are today a number of reasons why financial problems of utilities are particularly acute.

Inflation. In 1968, Georgia Power paid slightly over $7 per ton for coal, whereas the 1972 price is over $10 and is rising. As a general rule, the cost of capital per kilowatt of installed generating capacity has quadrupled in the past 10 years.

The electric industry's heavy reliance on debt financing. From 1960 to 1965, investor-owned electric utilities, on the average, had to finance externally only a little over 43 percent of construction requirements, and debt ratios remained relatively stable at around 52 percent of capitalization. However, construction expenditures skyrocketed during the latter half of the decade, resulting in the industry financing externally more and more in the form of long-term debt.

The inability of current technological developments to offset the continuing cost increases. After World War II, electric utilities were able to capitalize on technological improvements in steam generating units, which resulted in more efficient consumption of fuel. Raising the scale of operations became not only more feasible but also economically attractive. From this point, the size of units became larger and larger, which resulted in a lower initial cost per kilowatt. Unfortunately, larger units have a much higher probability of mechanical difficulties, and the increasing economics of scale have been highly exploited. The decline in heat rates has apparently ended, and future efficiency gains will be largely offset by rising plant costs.

Environmental demands. Although the electric utility industry has been concerned with environment protection for many years, the continually escalating demands for improvement have had a significant impact on the design, on the siting, and, inevitably, on the cost of new facilities. These expenditures are necessary, but they are an additional cost of generation that produce no offsetting revenues, and they thereby reduce the existing economics of operation.

Regulatory lag. This is a major factor. The problem arises with the lag between the time a request, based upon a recent test year, is first presented and the time rates actually go into effect. In some situations, this has taken as much as two years.

The end result of these factors is an unprecedented pressure on corporate liquidity, the company's ability to meet cash needs on time.

Our problems are many, but what about the future? Regulatory commissions are a key element in the resolution of the problems facing the industry. Their responsibilities have been increased tremendously and will continue to grow in the future. Innovations will be required to assure that utilities get the dollars needed to provide adequate service; historical ratios will not do the job. It is incumbent upon utility management to convince regulators that sound long-term solutions must prevail over short-term expediencies.

Investors are also an important consideration in solving our problems, for they will be called upon to invest billions of dollars to support rapidly escalating construction programs. Utilities have been out of favor on Wall Street, but we must have investor support in the future. Utility management must convince investors that the difficulties have been recognized and are being overcome.

An Overall View. Gerard C. Gambs, vice-president, Ford, Bacon & Davis: The energy crisis in the U. S. is being made even more critical because we are unable to get the nuclear-plant program operating on schedule. We are behind schedule by 15,000 MW as of Jan. 1, 1972, and from all indications will be behind by 30,000 MW by the end of 1972.

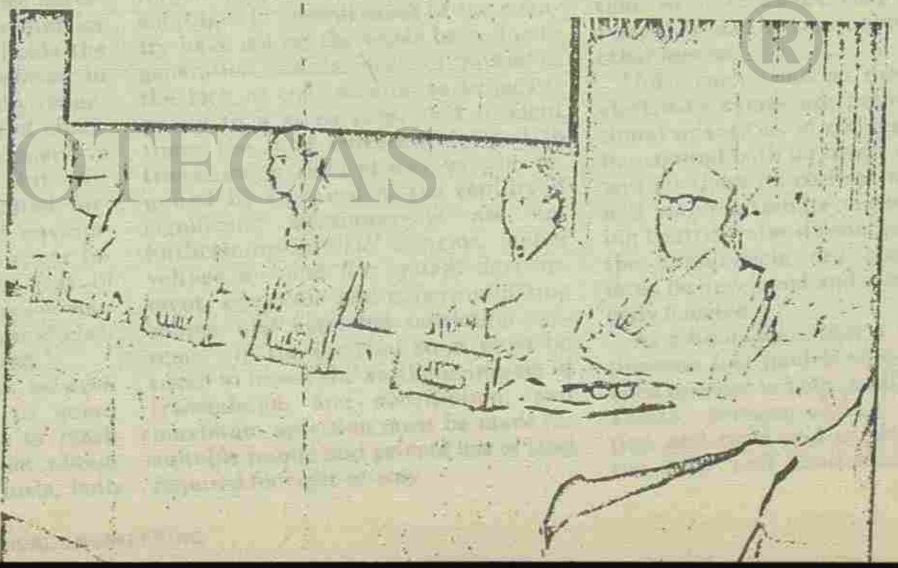
The impact on an already stretched fossil-fuel supply is very serious. The effect of a slowdown of each 10,000 MW of nuclear-power-plant capacity is that an additional 100 million bbl of oil per year must be found and burned. Therefore, the current annual shortage is about 300 million bbl, or nearly 1 million bbl per day.

By 1980-1985 we will be able to supply only 55 to 65 percent of our total energy requirements. The balance will have to be obtained through imports, or if we are unable to import this much oil and gas, we will have to do without it.

The agencies that have brought about the present energy crisis in the U. S. are as follows:

Rush Moody, Jr., addresses one of "The Energy Crisis" panels. He presented the government view.

Defining the Crisis. From the left: W. M. Jackson (who acted as moderator), W. D. Crawford, David C. White, Allen B. Wilson, Gerard C. Gambs.



Federal Power Commission. This agency has regulated the ceiling price, at the wellhead, of natural gas for interstate shipments. As a result of keeping the price of natural gas at a fraction of its real worth in the marketplace, the use of gas expanded beyond its normal sphere and displaced other fossil fuels, principally coal. However, the artificially low price set by the FPC was not sufficient to make it economic for more drilling to be done in search of gas. The reserve-production ratio declined steadily during the past two decades, and now the reserves of gas are in peril.

Atomic Energy Commission. The AEC has delayed construction permits for months, and the failure of the AEC and the administration in Washington to move ahead faster with the breeder program can only be described as criminal. The nuclear-power program, without a number of breeder plants by the mid-1980s, will be a failure.

Environmental Protection Agency. The EPA is undoubtedly more to blame for the present energy crisis than any other federal group. The performance standards for air quality that have been put into effect by the EPA have created massive repercussions in fuels supplies and uses. The EPA has caused high-sulfur coal to be unusable in many parts of the country. Is it any wonder that the coal industry is reluctant to invest millions of hard-earned dollars in the development of new coal mines?

Federal Trade Commission. The FTC has been trying for years to make a case for separating coal companies from oil companies and mining companies that had acquired them. The FTC contends such acquisitions have resulted in less competition, since energy companies dealing in oil, gas, coal, and uranium were formed by these acquisitions.

Contrary to the FTC's contentions, the acquisitions of coal companies have strengthened the coal industry by an infusion of vast sums of capital that were spent for developing new mines and new mine capacity. Without these funds, the coal industry would not have survived the past few years.

Simple logic must tell us what is going to happen if the present trends continue:

- A sharp reduction in the availability of oil, gas, and coal, leading to a cessation of all industrial plant expansion unless the company involved has a captive source of energy, preferably within the state that involves the expansion.
- Rationing of all fuels will become the order of the day. Natural gas that is in interstate commerce will be prohibited for industrial and power-plant uses.
- Sulfur restriction on fuels will be eased, but this will happen too late to have any effect on availability of coal, for example. New coal-mine capacity will not appear because of the transient nature of its requirement.
- Unemployment will reach unbearable levels as a result of the slowdown in the economy because of the shortage of energy.
- Blackouts and brownouts will occur because of lack of sufficient generating capacity.

The current problems, mainly environmental, are preventing the licensing of nuclear plants and fossil plants, and this will mean that by the summer of 1973 many parts of the U. S. will be without sufficient reserve generating capacity.

Short-Range Solutions

A Utility View. John Tillinghast, executive vice-president for engineering and construction, American Electric Power Service Corp.: The required near-term developments in electrical-energy field technology lie in four areas: energy conversion, transmission and distribution, environment, and systems.

In the energy-conversion area, expansion of existing fuel supplies, particularly coal, and development of new energy sources are required. The nuclear breeder reactor must demonstrate its viability by the period 1985 to 1990, thereby providing a means for slowing the drain on both fossil and nuclear fuel supplies. Further development of magnetohydrodynamics should be pursued. MHD holds the promise of improved efficiencies in fossil-fuel combustion (thereby reducing thermal discharges) and of elimination of the massive machinery in today's turbogenerators. But the long-term promise of unlimited fuel supply and greatly reduced environmental impact is held by nuclear fusion. Hopefully, within the next 10 years the feasibility of the fusion concept for continuous generation of electric power will be demonstrated.

To bridge the time gaps between these concepts and also to guard against the failure of any to reach commercial reality, we must obtain more supplies of available fuels, both fossil and nuclear. To a large extent this can be encouraged with the development of a rational national energy policy. Technology must also be advanced in the area of combined-cycle generating plants and in coal gasification for conventional and gas-turbine power plants. Progress must also be realized in light-water-reactor technology. Improved licensing techniques must be instituted. Improved efficiencies in fuel processing and fuel transportation are required.

The continued growth in the use of electrical energy will require more and higher capacity transmission and distribution systems. It is exceedingly important to recognize that energy shortages in several areas of the country have not on the whole been due to generation deficiencies but rather to the lack of transmission to bring capacity to a given area. Six to eight times the land currently devoted to transmission right-of-way will be required by the turn of the century if significant advancements are not forthcoming in UHV systems, higher voltage a-c and d-c system development, cryogenic and superconducting cables, and extended insulation systems. In the interim, steps must be taken to lessen the aesthetic impact of transmission and distribution, and maximum provision must be made for suitable public and private use of land required for right-of-way.

We in the U. S. have a great propensity to legislate away problems by making the symptoms illegal, rather than by attacking the basic causes. We have gone far down this road in environmental legislation, without the public understanding the costs and the effects on public demands of such legislation.

In the area of air quality, removal procedures for particulates and sulphur and nitrogen oxides must be determined, and commercially feasible emission-control systems must be developed. Methods must be developed for disposing of these pollutants once they are removed from power-plant stacks or from fuels prior to combustion, so as to assure they do not adversely affect the environment through other means.

Until such time as direct fuel-to-electricity cycles are perfected, additional quantities of cooling water will be required both for direct-cycle plants and for those on cooling towers. New and viable alternate methods of cooling heated-water discharges, including the closed-cycle dry cooling tower, must be developed and made economically feasible.

As a final suggestion, a series of nationwide fuel models should be developed in order to help predict fuel availability, transportability, characteristics, and costs and to help determine the type and limitations of future energy-conversion cycles. Overall power-system models are required to simulate the energy conversion, transmission, and distribution functions from the fuel to the consumer.

Congressional View of Siting. The Honorable Clarence J. Brown of the U. S. House of Representatives: Why is Congress considering the need for federal legislation to control the siting of power plants? That question can be answered in two words: demand and environment.

On the demand side, electric-power use in the U. S. has been doubling about every 10 years for several decades. This trend will continue, and perhaps even increase. Today electricity makes up roughly 25 percent of all energy consumed, and it is estimated that by the end of this century *one-half* of our total consumption of energy will be in the form of electricity.

In absolute terms of power-production needs, what does this mean? It means that over just the rest of the current decade—less than eight years—it is estimated roughly that we must construct the equivalent of 150 new power plants, each capable of producing 500,000 kw of electric power. Between 1980 and 1990 the outlook is the same—another 150 plants rated at 500,000 kw each will be needed.

That brings us to the other side of the question: environment. Environmental concerns have had a great impact on the construction of new electrical generating plants during the past several decades. The classic case is at Storm King Mountain on the Hudson River in New York. It has been more than 10 years since Consolidated Edison first applied to the FPC for a license to build the plant. Before the full gamut of litigation precipitated by monumental pressure is run, several more years of delay may accrue. Even if such proposals escape the courts, the problems of obtaining a site and construction permit often represent costly and time-consuming obstacles.

Commissioner James T. Ramey of the Atomic Energy Commission pointed out last summer that the dollar cost of power-plant construction delays can run as high as $50,000 to $100,000 per day per plant, covering such items as interest on construction loans, loss of revenue, cost of purchasing outside power (if available) to meet demands, and cost of attorneys' fees, consulting engineers, and others directly involved.

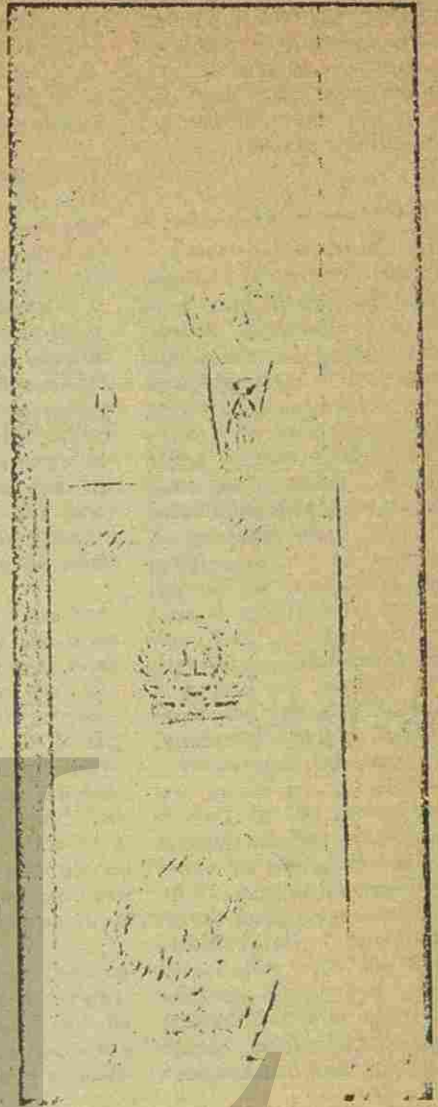
There are also indirect losses in tax revenues, inconvenience (and even dangers) to the public inherent in brownouts and blackouts, and hardships in a community resulting from inadequate power for public services (including pollution abatement), all of which are harder to measure.

But while serving the environmental concerns, we must also serve the public need for power—much of which, in fact, is necessary for the protection of the environment.

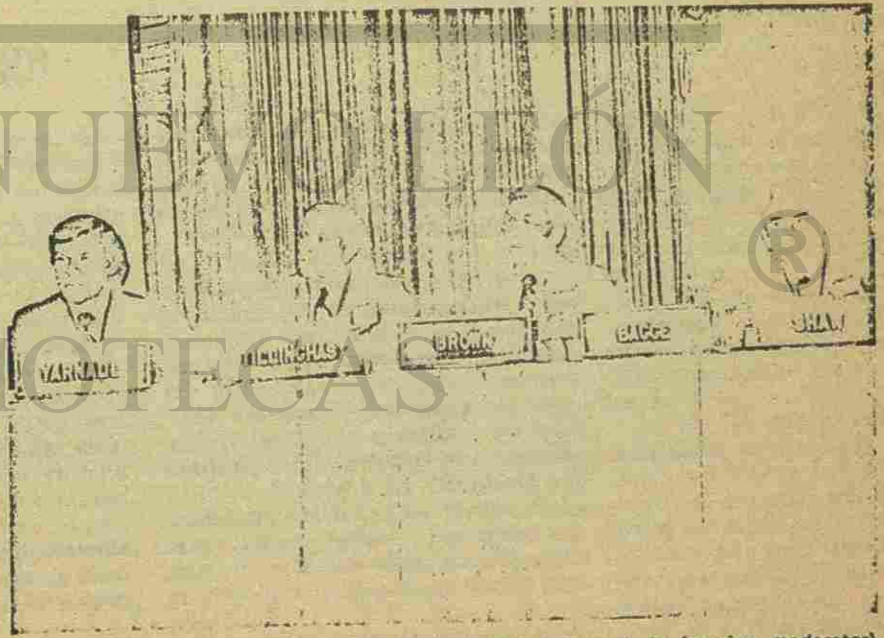
Lots of people, including well-meaning environmental activists, are using virtually every means available to halt increased electric production capacity, and they fail to see the connection between the power plant and the home wall socket, the kitchen trash masher, the subway system, the sewage-treatment plant, or even the power plant itself. Yes, the power plant, too. It requires approximately 9 to 10 percent of the generation capacity of the average plant to run cooling towers required to reduce thermal pollution, if cooling towers are required. In smoke-emitting plants, 3 to 4 percent of the output may be required to operate the precipitators needed to clean up the stacks.

I am not against the environmentalists nor our efforts to clean up and protect the environment. That is a national priority that should get more attention, not less. And that is exactly one of the major reasons why we must have an overall national power-plant-siting policy. Such an "umbrella" policy would put environmental considerations into an orderly schedule that would enable us to compress the time that is now wasted in procedural and jurisdictional maneuvering that arises when controversies over siting develop. The enactment of federal legislation would bring long-range planning, review, certification, and licensing procedures under a comprehensive and workable plan.

How do we get from here to there? The effort was initiated in 1968 when



Carl E. Bagge, addressing the energy session on "Short-Range Solutions." He presented a fuels view.



"Short-Range" Symposiasts. From the left: D. Robert Yarnall, Jr. (session moderator), John A. Tillinghast, Congressman Clarence J. Brown, Milton Shaw.

President Johnson established the Federal Interagency Power Plant Siting Group (composed of AEC, FPC, NAPCA, REA, TVA, the Office of Science and Technology at the White House, and the Department of the Interior). The group submitted two reports—in January of 1969 and August of 1970—which came up with a four-point set of conclusions and recommendations for resolving the siting problem. They were:

1 Long-range planning of utility expansions on a regional basis at least 10 years ahead of construction.

2 Participation in the planning by the government environmental protection agencies *and private organizations* and notice to the public of plant site locations at least five years in advance of construction.

3 Pre-construction reviews and approval of all new large power facilities by a public agency at the state or regional level, or by the federal government if the states fail to act.

4 An expanded program of research and development for power production and transmission.

A Fuels View. Carl E. Bagge, president, National Coal Association: Coal is the one fuel that can, if it is allowed to, provide both short- and long-term solutions to the country's energy crisis. The industry must, however, be freed from excessive restrictions if its potential for providing ample supplies of clean energy is to be realized.

As the country faces an impending energy crisis, the coal industry is facing a short-term crisis of its own. Energy experts are predicting a rising demand for coal both in its present form and as feedstock for gaseous and liquid fuels, but the industry is presently beset by an environmental nemesis which is seriously impairing its ability to perform useful service.

Having just regained a firmer footing after years of setbacks, the coal industry is now beginning to teeter under the pressures exerted upon it by the Clean Air Act of 1970 and the public outcry against strip mining.

We must forge a set of energy priorities which take into serious account the quality of our air, land, and water, but this effort must be made within the parameters of our available energy supplies and our relentless energy demands. The attacks on the coal industry threaten to weaken our most plentiful fuel source at a time when we are running woefully short of other domestic fuel reserves.

State air regulations which are banning the use of coal by electric utilities must be eased if the country is to meet its immediate fuel shortages with domestic resources. While this proposal may sound an unpopular note in the environment camps, it is, if the country is to remain independent, a necessary one. We must bear in mind that the easing of these regulations is a temporary measure—one which places our concomitant search for adequate energy and clean air in the sphere of reality rather than illusion.

Granted the necessary stay, the coal industry, in conjunction with government and other industries, will be freed to pursue the research necessary to bring coal into the realm of a clean-burning fuel. Solutions to the energy crisis will be effected with coal through development of equipment for removal of sulfur dioxide, by bringing synthetic gas from coal from research to the commercial stage, and by opening up the vast western reserves of low-sulfur coal.

A Nuclear Proponent. Milton Shaw, director, Division of Reactor Development and Technology, U. S. Atomic Energy Commission: In the search for solutions to the problems of energy and environment, full use must be made of both traditional energy sources and advanced technologies. Nuclear energy offers important benefits in helping meet energy needs: it helps conserve other fuels for purposes for which they are uniquely suited; it provides a competitive source of energy with costs that do not vary appreciably with location; it significantly reduces the problem of air pollution and has other important environmental advantages; it is a positive element in our foreign trade and provides freedom from over-reliance on foreign sources.

While coal, oil, gas, and hydroelectric power are projected to continue sharing in the growth of the energy market, nuclear energy can and must make an important and eventually a vital contribution toward meeting our future energy requirements in an environmentally acceptable manner. Experience with the development of nuclear power has clearly demonstrated that bringing in any new major energy technology is an extremely complex and costly undertaking.

The Long Range

A Utility View. W. B. Behnke, vice-president, Commonwealth Edison Co.: Ten years ago about 18 percent of our primary energy was used to generate electricity. Today about 25 percent is used, and by 2000 we expect it to be about 50 percent.

First, what is the outlook for energy demand? Per capita energy consumption in the U. S. is expected to increase about 2 percent annually for at least the next several decades. Population will probably grow at a similar rate. As long as these rates of growth hold true, overall energy demand in the U. S. will go up between 3 and 4 percent annually, and world requirements may exceed that rate, depending upon what happens in the underdeveloped nations.

Fossil fuels currently supply about 96 percent of our domestic primary energy needs and will continue to be an important source for the rest of this century, even though nuclear fuel will supply an increasing share of the total.

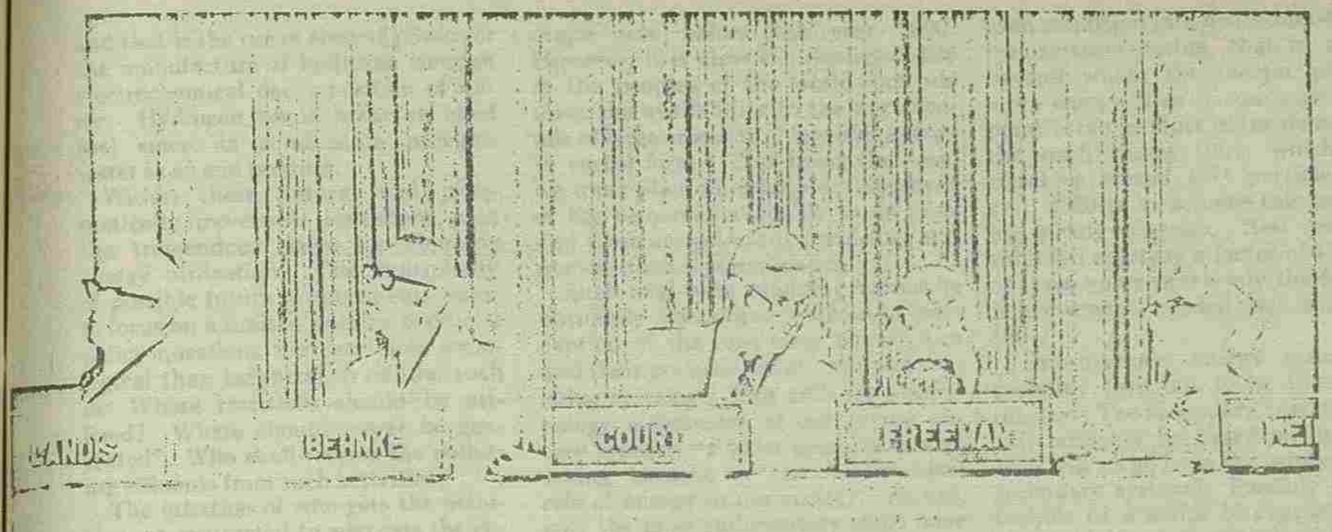
The oil and gas outlook is pessimistic. Domestic reserves are limited. Fuel imports offer some relief but pose problems for national security and also hurt our balance of payments. But precious hydrocarbon resources are more than mere latent calories. They are rapidly becoming too valuable to be burned directly. We must begin to think in terms of conserving them as feedstock for chemicals and foodstuffs which will be needed in the more distant future. For these reasons, it is critical that we seek other sources for our long-range energy supplies.

Second, what are the options for assuring adequate supplies of clean energy in the future? There are many, and they include the following:

1 For the immediate future, available uranium resources can be expanded by lifting the foreign embargo and expanding the U. S. enrichment capability.

2 We can move ahead with demonstrating the breeder, and we are doing this on a top-priority basis, aiming at having this technology available in the 1980s.

3 We can develop environmentally acceptable ways to mine oil, shale, and coal, and we can perfect coal gasification and liquefication systems to expand fossil-fuel availability, but these methods will take time to develop. In the meantime, we will do well to critically reappraise the potential of the technology being developed for removing sulfur oxides from flue gases. Per-



The "Long-Range" Panel. From the left: John W. Landis (session moderator), W. B. Behnke, Jr., John Court, S. David Freeman, Alvin M. Weinberg. Another panelist (not here shown) was Chauncey Starr.

haps we should adopt the British system of using high stacks as the most feasible way of dealing with stack gases until reliable and economically feasible stack-gas cleanup systems, or some other alternative, can be perfected.

4 We can get on with developing entirely new energy systems such as fusion, hydrogen, solar, and geothermal power as a means of assuring adequate supplies of clean energy into the far-distant future.

5 Efforts must be made to further improve the efficiency of energy utilization.

Tremendous amounts of capital will be needed to pay for the needed research and development and to finance expansion of future energy systems. It is estimated that the industry's total capital requirements will be on the order of $400 billion to $500 billion, valued at 1970's prices, between 1970 and 1990.

We think the utilities will turn increasingly to nuclear power in the decades ahead, and with the breeder, nuclear power will account for a growing share of our domestic energy production. Over the longer term, however, new technology will probably favor the fusion reactor employing direct conversion to electricity at some point. Fusion looks like the brightest long-range prospect for substantially increasing the energy supply. A combination of the breeder and fusion would supply us with an almost limitless amount of energy.

Our model for the remainder of this century envisions large dispersed energy-conversion centers. Regional grids of EHV and UHV transmission will interconnect these centers with urban markets.

A Scientist's View. Chauncey Starr, dean of the School of Engineering and Applied Science, University of California at Los Angeles: Since 1900 the average per capita energy consumption in the world and in the U. S. has doubled every 50 years, with some short-term perturbations. There appears to be small likelihood that this long-term trend will change markedly in the next several decades, because of the balancing of pressures.

In the development of future concepts for our energy systems there are a number of constraints established by nature. The most obvious of these is the depletion of resources for energy production. The depletable supply of fossil fuel certainly appears adequate for some period beyond the year 2000, both for the world and for the U. S. As has often been stated, nuclear fission provides another major resource—with the present light-water reactors about equal to the fossil fuels and with the breeder reactors almost 100 times as much. The continuous supply of solar energy is, of course, an enormous resource we still do not know how to tap effectively. There is also the internal heat of the earth, in the form of steam, hot water, and hot rock.

For the next half century, mankind is unlikely to run out of available energy. Instead, the important issue is whether the increasing cost of energy (including environmental costs) will handicap societal improvement.

Another natural constraint arises from waste-heat dissipation. This problem will always be with us and cannot be removed by technological ingenuity—all energy use eventually ends up as heat. All that technical development can do is to alter its area concentrations. However, the solar heat load on the atmosphere is so great that the incremental contribution likely to be made by man is not an important fraction thereof. What is of importance is the geographic and urban concentrations of energy dissipation which may alter natural and urban environments. Heat dissipation may be one of the long-range limitations on urban population density. At the present average U. S. energy dissipation of 10 kw thermal per capita, a population density of 30,000 people per square mile (half New York City's density) will produce waste heat equal to the average solar heat loading of the atmosphere.

Of the uncertain natural limitations, the effect of carbon dioxide—which is an inevitable end product of fossil-fuel utilization—is as yet a long-term environmental mystery. We do have at least several decades for determining the closed CO_2 cycle in our biosphere and the equilibrium relationships. The alleviating development is the use of nuclear power. Nevertheless, it appears that we will always need a combustible fuel, and certainly for several centuries this is likely to be a hydrocarbon in some form. If, however, the CO_2 problem were determined to be serious on a worldwide basis, there is an ultimate but very costly technological solution, and that is the use of electric power for the manufacture of hydrogen through electrochemical decomposition of water. Hydrogen would make an ideal fuel since its combustion provides water as an end product.

Within these natural and pragmatically irreversible limitations, man has tremendous scope for planning energy utilization. The multiplicity of possible future arrangements tends to focus on a limited number of crucial policy questions that are more sociological than technical in nature, such as: Whose resources should be utilized? Where should power be generated? Who shall receive the polluting effluents from such activities?

The question of who gets the pollution, as contrasted to who gets the energy, is not only one of geographic distribution but also of time. For example, if as a result of the rapid increase in strip mining for coal, acid drainage and soil erosion destroys the ecology of large regions, it may take decades to repair the damage in spite of extensive restorative efforts by the coal-mining industry. This generation of energy users will be long gone when the next generation faces the problem and the cost of repairing damage of such ecological deterioration.

If, as a result of the effluents produced from energy conversion, we produce environmental damage which may have genetic consequences, we also face the problem of distributing the pollution effect through time. For example, if the waste emissions from both fossil-fuel and nuclear power plants are permitted to pollute the environment, the consequences may not be serious in this generation, but they might be in the next because of delayed genetic effects. Fortunately, this problem has been thoroughly studied, and reasonable technological controls can remove this issue.

Perhaps the most fundamental question of national planning is the allocation of our present resources for the benefit of future generations. In the technological domain of new energy devices, we are really working for the next generations, rather than for our own. Even nuclear power, which was certainly supported by government as enthusiastically as any technology in history, has taken 25 years to establish a commercial base, and it still hasn't made a real impact on our energy supply. So the development of new speculative energy resources are investments for the future, not a means of remedying the problems of today. The attraction of "jam tomorrow" may persuade us to neglect the need of "bread and butter today." Because of the very long time required for any new energy device to become part of the technological structure of our society, even if successful these speculative sources could not play a major role before the year 2000. However, it is clear the quality of life of the peoples of the world depends upon the availability in the next decade of large amounts of low-cost energy in useful form. This being the case, we must plan an orderly development of the resources available to us now, and these are primarily fossil-fuel and nuclear-fission power plants.

Such near-term planning cannot be optimally conducted without a perception of the long-term possibilities and their potential relationships to existing systems. This calls for a technology assessment of our future energy systems—a most complex undertaking because of the fundamental role of energy in our society. As yet, only the most rudimentary steps have been taken toward such an assessment.

A Technological View. Alvin M. Weinberg, director, Oak Ridge National Laboratory: Until new knowledge is available, work on the development of solar energy is a waste of time.

The design proposed by a group headed by Aden Meinel of the University of Arizona is imaginative but is probably too costly ($1000–$3000/kw). This reduces to roughly 2.7 ¢/kw. Meinel's scheme would use Fresnel lenses to focus sunlight onto a stainless-steel or glass-ceramic pipe, concentrating the solar flux about 10 times its normal value. The pipe, covered with a selective coating that emits only a small proportion of the energy it absorbs, is enclosed in an evacuated glass chamber to reduce conductive and convective heat losses. Nitrogen gas pumped through the pipe transfers the heat from the collectors to a central storage unit. The heat would then be used to produce steam for a turbine as needed.

For the short range, we can use geothermal resources. There are three: hot steam, hot water, and hot rock (by far the largest). Hot rock is particularly attractive because it can be utilized anywhere.

Tapping this heat can be done in the following manner: Two wells are drilled, one to 15,000 ft and the other to 12,000 ft. Hydraulic fracturing would then be used to create a large heat-transfer bed between them. Water would be pumped down the first hole. It would be circulated through the underground fracture system where it would be heated and then forced up through the second and shallower hole to the surface. We will have fusion power at some time *X*—perhaps by the year 2000, perhaps later—but we can't base an energy policy on this prospect.

Laboratory success of fusion depends on meeting Lawson's criterion. This is the point at which a break-even condition in a deuterium–tritium fuel mixture occurs, that is, a point beyond which the reactor produces more energy than it consumes. This point is the product of the density and the confinement time, which must equal or exceed 10^{14} particle-sec/cu cm. Efforts to achieve this are making steady progress. Best recent results fall short by a factor of 10. Two or three years previously the factor of improvement needed was more like 100.

The ultimate energy system will probably turn out to be the breeder reactor. The secondary energy system will probably be based on hydrogen. How will we go from the primary to the secondary system? Possibly by electrolysis or a series of coupled closed chemical reactions with heat the only input (temperatures no higher than 800 C). Hydrogen may also be produced through a biological system, using sun or bacteria as catalysts, working on water.

As far as the dangers of a breeder system, engineers must demonstrate a commitment to excellence so that power can be used with a high degree of security.

The Government View. John Court, deputy assistant administrator for planning and evaluation, Environmental Protection Agency: As major changes in prices occur, the nature of the energy crisis will undergo big change. There will be a greater supply because of higher prices, and new forms of energy will be developed because higher prices will facilitate their economic development.

A Public View. S. David Freeman, project director, The Energy Policy Project, Washington, D. C.: There will be a fundamental change in energy supply in the next decade. A consequence will be a sharp increase in price after decades of consistently stable and low-priced energy. Long-term solutions to the energy crisis must be planned now. Finding energy for the 1980s and 1990s must be on our current agenda.

The world won't tolerate the U. S. wasting a major part of its abundant energy while there are grave shortages in the rest of the world. The U. S. must, therefore, improve efficiency of energy use (at present, our transportation system runs with an efficiency of only 6 percent, considering all links in the energy chain). The government program must be on the level of the Apollo program—R&D in the billions are needed, in solar, geothermal, fusion, etc.

As Pogo says: "We have met the enemy and they are us."

BOON TO SOCIETY:

THE LMFBR

The world can reap tremendous benefits in terms of greatly increased energy resources from the liquid-metal fast breeder reactor (LMFBR). Here's a rundown based on the Westinghouse design prepared during the project definition phase of the LMFBR demonstration program of the U. S. AEC.

R. J. CREAGAN[1]

Westinghouse Electric Corp., East Pittsburgh, Pa.

Society on a worldwide basis will benefit from decisions now being made by industry and government with respect to development of the liquid-metal fast breeder reactor, which will be implemented in the 1970s in the U. S., England, Russia, France, Germany, and Japan.

How will society benefit? Stated simply, the LMFBR converts more of the heat it produces to electricity than water reactors because of its greater thermodynamic efficiency—40 percent compared with about 30 percent for the light-water reactor. It has a thermal discharge of 4800 Btu/kwh versus 6600 for the light-water reactor. This is approximately 30 percent less heat rejection to the environment for an LMFBR than for a water reactor. Since neither water nor LMFBR reactors will release noxious chemicals, thermal discharge is the principal difference in environmental effect between the two types of reactors. Other than heat rejections, the nuclear plant has essentially zero effect upon its environment, and thus is indeed a good neighbor and a benefit to society.

Seven LMFBRs are currently operable, six are under construction, and nine are in the planning stages. As an indication of the intensity of international efforts, the planned expenditures for LMFBR development programs for the various countries and their gross national products are listed in Table 1.

Another measure of LMFBR importance in the U. S. is project cash flow, which will be approximately $500 million for the first demonstration plant from 1972 through 1978. Later, about 3000 MWe of LMFBR capacity will be committed in the 1970s, which at $400 per kw is a billion dollars.

As evidence of U. S. LMFBR policy, President Nixon, in his June 4, 1971, energy message to Congress, stated that "our best hope today for meeting the nation's growing demand for economical, clean energy lies with the fast breeder reactor." The president further gave a commitment to complete successful demonstration of the LMFBR by 1980, and

TABLE 1 National Investments in LMFBR

	Country					
	U. S.	U.S.S.R.	France	U. K.	Japan	Germany
LMFBR/year ($ millions)	200	200	100	70	50	30
1972 GNP ($ billions)	1113	538	162	128	232	195
Percentage of GNP	0.018%	0.04%	0.06%	0.055%	0.02%	0.015%

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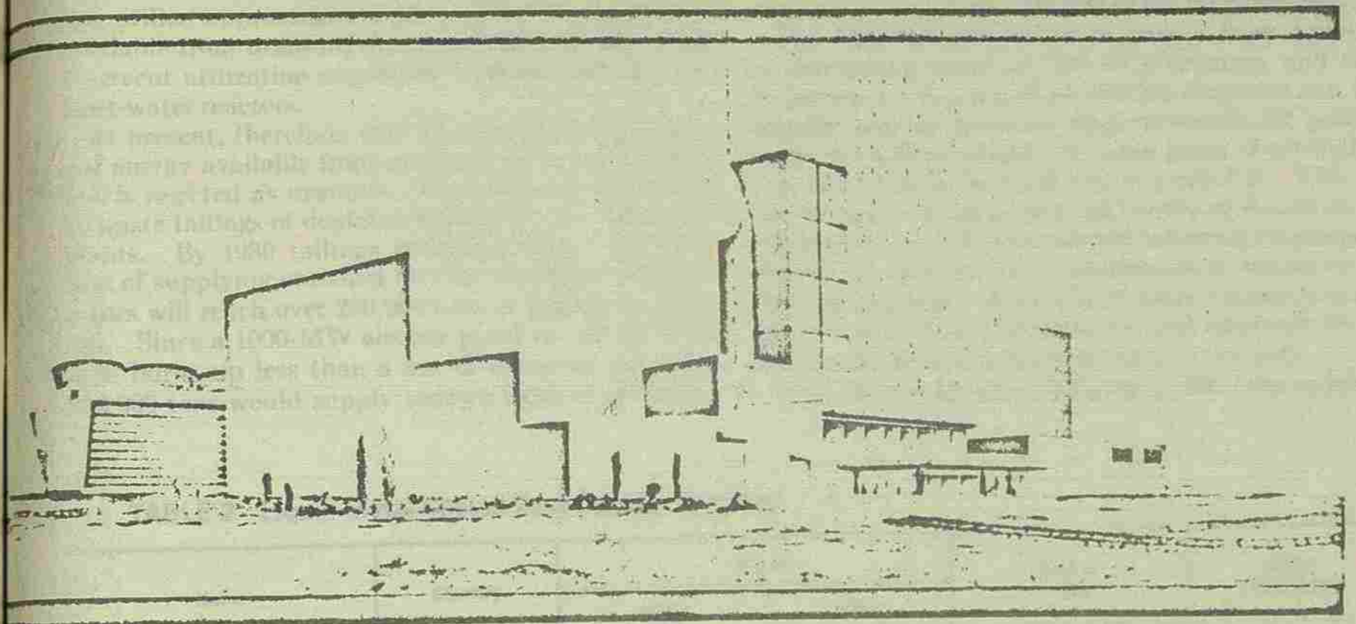
[1] Manager, R&D Planning.

Based on a paper contributed by the ASME Aerospace Division.



later (Sept. 26, 1971) in a speech at Hanford, Wash., indicated that there should be two demonstration plants.

Financial benefits to society from the LMFBR might best be summarized by an AEC cost-benefit analysis which indicates benefits to the nation over a 34-year period of $21.5 billion, discounted at 7 percent to mid-1971. Other specific LMFBR benefits to society will be described in the sections that follow.

The Plans for LMFBR Plants

World status and plans for LMFBR power plants are given in Table 2,[2] which lists LMFBR projects that are operable (7), under construction (6), planned (9), and decommissioned (4), with country location, megawatts thermal and electric, and initial operation date. Table 2 also shows whether a loop or pool configuration is used.

Present plans for the U. S. LMFBR program in the 1970s consist of completion of the 400-MWt Fast Flux Test Facility (FFTF) on the AEC's Hanford Reservation in the state of Washington. It will not produce electric power but will reject heat to an air heat exchanger. Its development will provide base technology applicable to LMFBRs and associated industry experience needed in order to supply the components and systems for such a plant. The reactor will contain closed loops for advanced fuel tests, which will be isolated from process sodium in the main reactor coolant loop so that test failures will not harm the reactor.

In addition to FFTF, the highest priority U. S. LMFBR program for the 1970s is construction of the two demonstration plants mentioned by President Nixon.

The request for proposal for the first demonstration plant specified a power level between 800 and 950 MWt (approximately 350 MWe). Approximately $400,000,000 has been committed for development, design, construction, and testing of this project by the Atomic Energy Commission, the utility industry, and the future owner-operators, TVA and Commonwealth Edison.

Power output for the second demonstration breeder reactor has not yet been specified, but the unit will probably be larger, with authorization arranged after the first demonstration plant is committed for construction and funding. AEC authority under the project definition phase permits some work on a second plant. The ultimate objective of the cooperative government-utility-industry program is to develop a competitive, viable, and economic industry in the U. S.

In contrast to the lead which the U. S. had in water-reactor technology, we now have comparable technology in the sodium-reactor field with Russia, England, and France but are behind them in plant construction schedules.

Worldwide interest and investment is motivated by LMFBR ability to provide essentially limitless electric energy from fuel which can be imported easily and self-generated. The LMFBR does not place the country using it at a political or economic disadvantage with respect to another country by requiring a continuing supply of either large amounts of raw material or an isotope separation process, as is the case with enriched-uranium reactors.

Available Nuclear Energy

The most important long-term advantage of the breeder is the increase in available energy it provides from nuclear resources. The fact that such additional energy is required is indicated by Table 3, which shows the growth in energy requirements as the population of the U. S. increases and more power is consumed per person. A similar pattern will be followed throughout the world with a greater percentage increase in developing countries.

The LMFBR will provide more energy because it

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[2] Figs. 1 and 2 and Tables 2 and 3 are from a statement of Milton Shaw of the AEC at FY 1973 authorization hearings before the Joint Committee on Atomic Energy, Feb. 22, 1972.

can utilize approximately 75 percent of the energy available from uranium ore compared with less than 2 percent utilization capability for enriched-uranium light-water reactors.

At present, therefore, over 95 percent of the potential energy available from uranium ore is not utilized but is rejected as uranium 238 in burned-out fuel or as waste tailings of depleted uranium at the diffusion plants. By 1980 tailings produced during the process of supplying enriched fuel for the light-water reactors will reach over 250,000 tons of depleted uranium. Since a 1000-MW electric plant of the LMFBR type burns up less than a ton of uranium per year, 250,000 tons would supply today's total U. S. power requirements of about 300,000 MWe for centuries.

The LMFBR obtains more energy from uranium by converting uranium 238 to plutonium and then fissioning it. A gram of plutonium fissioned in a fast breeder reactor provides approximately 50 percent more Btu's than would the same gram of plutonium if fissioned in a thermal neutron reactor. This occurs because of the greater efficiency of fission in the fast reactor, which does not permit as much parasitic absorption of neutrons in plutonium as occurs in the thermal reactors. Also, about twice as much uranium 238 is fissioned directly by fast neutrons in the fast reactor as in the thermal neutron reactors.

The thermodynamic efficiency for conversion of

TABLE 2 Liquid-Metal-Cooled Fast-Reactor Projects

Name	Country	Power		Pool or Loop	Initial Operation
		MWt	MWe		
Operable					
BR-5	U.S.S.R.	5[a]	—	Loop	1959
DFR	U. K.	72	14	Loop	1959
EBR-II	U. S.	62.5	16	Pool	1963
FERMI	U. S.	200	60.9	Loop	1963
RAPSODIE	France	40	—	Loop	1967
SEFOR	U. S.	20	—	Loop	1969
BR-60 (BOR)	U.S.S.R.	60	12	Loop	1970
Under Constr.					
BN-350	U.S.S.R.	1000[b]	150	Loop	1972
PFR	U. K.	600	250	Pool	1972
PHENIX	France	600	250	Pool	1973
FFTF	U. S.	400	—	Loop	1974
JOYO	Japan	100[c]	—	Loop	1974
BN-600	U.S.S.R.	1500	600	Pool	1976
KNK-11	W. Germany	58	20	Loop	1973
PEC	Italy	140	—	Modified pool	1976
SNR	W. Germany[d]	730	300	Loop	1977
DEMO NO. 1	U. S.	750-1250	300-500	Loop	1977
MONJU	Japan	750	300	Loop	1978
DEMO NO. 2	U. S.	750-1250	300-500	Not decided	1979
CFR	U. K.	3125	1320	Not decided	1979
PHENIX 1000	France[e]	2500	1000	Pool	1979
SNR 2000	Germany[e]	5000	2000	Loop	1983
Decommissioned					
CLEMENTINE	U. S.	0.025	—	Loop	1946
EBR-I	U. S.	1	0.2	Loop	1951
BR-2	U.S.S.R.	0.1	—	Loop	1956
LAMPRE	U. S.	1	—	Loop	1961

[a] To be increased to 10 MWt in 1972.
[b] Dual purpose; 150 MWe for electric power and 200 MWe equivalent for desalination.
[c] To be operated at 50 MWt initially.
[d] In cooperation with Belgium and The Netherlands.
[e] Tripartite effort: France, German and Italian electric utilities.

TABLE 3 U. S. Electric-Utility Power Statistics

	Actual			Projections for		
	1950	1960	1970	1980	1990	2000
Population (millions)	152	181	205	234[a]	270[a]	305[a]
Total power capacity (millions of kw)	69	168	340	665[b]	1260[b]	2100
kw capacity/person	0.45	0.93	1.6	2.8	4.7	6.9
Power consumed per person per year (kwh)	2200	4200	7300	13000	22000	33000
Total consumption (trillion kwh)	0.33	0.75	1.5	3.1[b]	5.9[b]	10[b]
Nuclear power capacity (millions of kw)	0	0.3	7.5	150	475[b]	1100
Nuclear power, percentage of total	0	0.2%	2%	23%	38%	50%

[a] Bureau of the Census Report Series P-25, No. 470, 11/71
[b] FPC.

heat to electric power in an LMFBR is 40 percent, as compared with the 33 percent typical for a light-water reactor; hence more electric power is produced per kilogram of uranium fissioned.

Economic Power

The key to the breeder's potential for low overall power-generation costs is its fuel cycle and high thermal efficiency. Whereas light-water-reactor energy is supplied mainly by fission of the rare isotope uranium 235, the breeder reactor is more economically fueled with plutonium and actually produces more than it consumes. With a breeding ratio of 1.3, the breeder produces 1.3 atoms of fissile plutonium from the abundant isotope uranium 238 for every atom of fissile plutonium it consumes, and thus doubles its inventory of plutonium approximately every 12 years.

Fuel-cycle costs are given in Table 4. As can be seen from the table, the fuel-cycle costs for the LMFBR are capital-intensive: the cost of plutonium inventory is the major component of the fuel-cycle cost. Because of this capital-intensive nature of the fuel cycle, the cost of incremental kilowatt-hours is very low; hence the LMFBR nuclear power plant will be dispatched on any power system as a base-load plant.

The statement is commonly made that the capital cost for the LMFBR power plant will be greater than that for a water reactor, and this is indicated by considerations of an additional intermediate loop of sodium as well as by learning- or experience-curve considerations. Market predictions are such that total megawatts of electric experience for the LMFBR might not be comparable with that of water reactors until the year 2000; hence the LMFBR will not have progressed as far down its learning curve as the water reactors until 2000. Despite these considerations, however, the unit costs of LMFBR heat-generating systems do not have to be as low as water reactors, since the LMFBR, because of its greater thermal efficiency, does not handle as much heat energy as a water reactor to produce the same electric power. Since the water reactor must produce approximately 30 percent more heat power than the LMFBR to produce the same amount of electrical power, the LMFBR capital cost per unit megawatt thermal could be 30 percent higher for heat-handling components of the LMFBR and still produce electric power with the same associated capital for total electric power plant. For these reasons, economic competitiveness of the LMFBR is considered just a question of time, development, and experience.

[illegible]

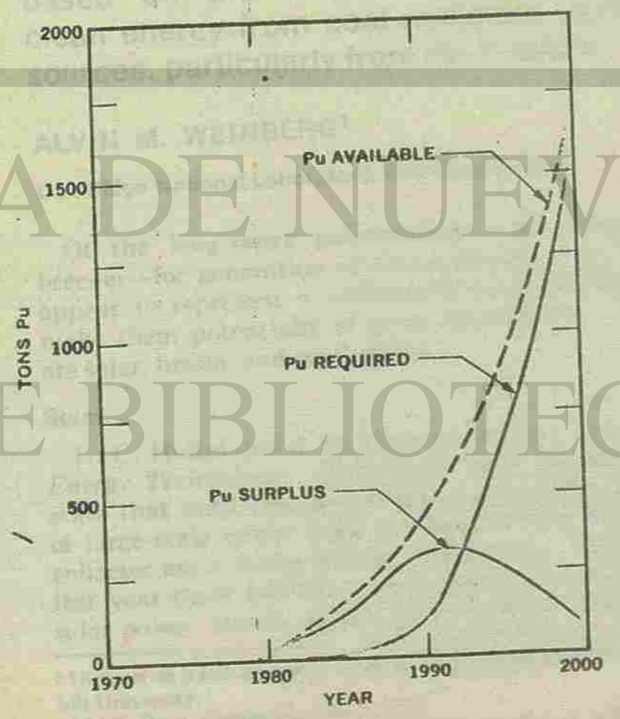
Capital Investment

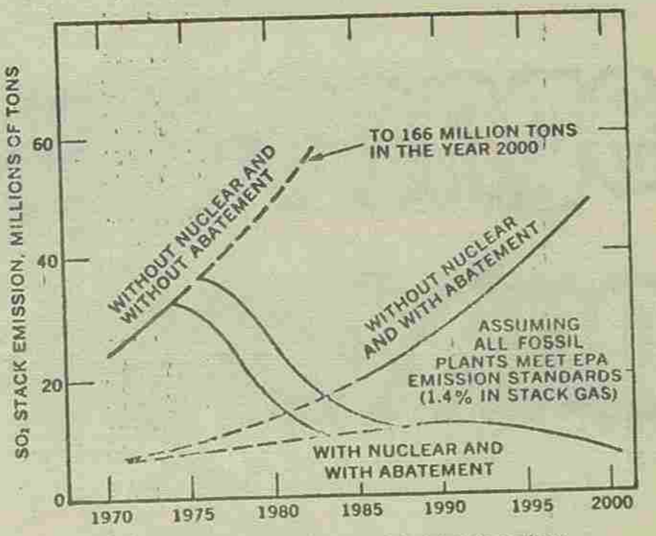
As breeder plants are put on line in the 1980s and 1990s and the effects of plutonium production are felt, the demand for enriched uranium and hence for uranium ore to feed the diffusion plants will increase less rapidly. This occurs not only because the fast breeder does not require enrichment from the diffusion plant but because the breeder also provides plutonium that can be utilized in the thermal reactors to provide enrichment instead of uranium 235 from the diffusion plants.

Plutonium available and required in the U. S. is given in Fig. 1. As can be seen, there is a surplus of plutonium with respect to inventory requirements for LMFBR reactors. In fact, LMFBR inventory requirements do not exceed the plutonium available from water reactors until the early 1990s, at which time excess plutonium from LMFBRs will provide inventory for new plants. This means that breeding ratios and doubling times for LMFBRs in the early years can be based on economic considerations rather than doubling time of the utility industry.

Since, as was mentioned before, approximately 250,000 tons of uranium will exist as tailings at the diffusion plants by 1980, this would supply all the uranium requirements of the fast breeder reactor for hundreds of years. The uranium hexafluoride tailings contained in cylinders at the diffusion plants are an energy source in proper chemical form waiting to be used for fuel processing and fabrication. As the uranium 238 becomes useful, it reduces requirements for prospecting for new uranium-ore reserves and the capital associated with putting in the mines and the chemical-upgrading plants associated with them.

Fig. 1 Plutonium availability.





(Source: Milton Shaw, statement to Joint Committee on Atomic Energy, Feb. 22, 1972.)

Fig. 2 Projected sulfur dioxide annual stack emissions from U. S. electric power plants.

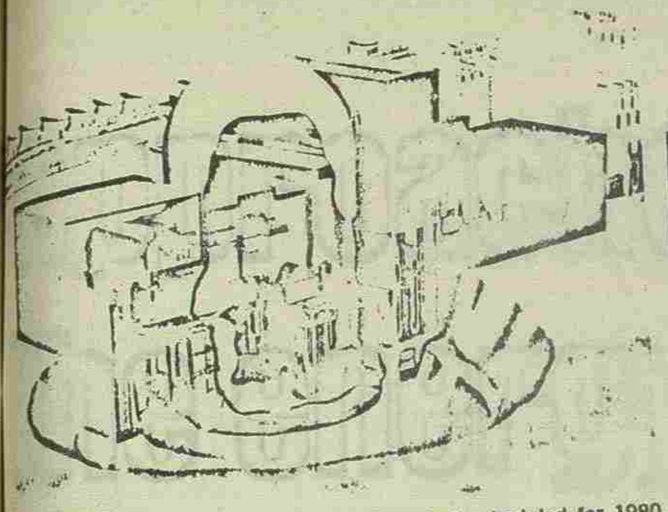
In addition, the need for additional isotope separation plants also decreases. Since the three diffusion plants built in the U. S. cost approximately $1 billion each, this is a major capital consideration. Put in other terms, about $15 capital is required in diffusion-plant capacity for each kilowatt electric of installed enriched-uranium reactors. This requirement will be eliminated eventually for the LMFBR. However, the LMFBR will not come on stream fast enough to influence separative work requirements until the late 1980s. If all water reactors were retired after 30 years and replaced by LMFBRs and all new capacity were supplied by LMFBRs, the diffusion-plant load would go essentially to zero in the year 2020. New isotope separation plants will be needed in the early 1980s and will not be influenced by the LMFBR.

Environmental Effects

Figure 2 shows the projected annual sulfur dioxide stack emission from U. S. fossil-fuel electric power plants and how it is reduced dramatically by nuclear power. The chemical-emission benefits claimed for nuclear occur whether the plant is an LMFBR or a water-type reactor, and the benefit is dramatic and can be useful to society.

Summary

LMFBR provides benefits to the world in terms of greatly increased energy resources. The additional energy supplements the fossil-fuel energy reserves and greatly increases the potential for production of useful power from the nuclear-energy reserves already available. A cost–benefit analysis by the AEC indicates benefits to the U. S. over a 34-year period of $21.5 billion, discounted at 7 percent to mid-1971. The higher temperatures involved provide greater thermal efficiency, which reduces the effect of heat rejection to the environment.



400 MW(e) LMFBR demonstration plant scheduled for 1980.

long-range resolving

Long-range possibilities for generation of prime energy (other than the nuclear breeder) are basically only three: solar, fusion, and geothermal. Predictions in favor of one or the other of these possibilities tend to take on the character of prophesy, principally because the prophet knows he will probably be dead by the time the returns are in. Fermi, for example, discussed the fast breeder, not expected before the mid-Eighties, in 1943. The prophets may be right, but a prudent overall energy policy must be based on the two firm alternatives—clean energy from coal and from nuclear sources, particularly from the breeder.

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Of the long-range possibilities—other than the breeder—for generation of prime energy, only three appear to represent a sufficiently large resource to make them potentially of great importance. These are solar, fusion, and geothermal.

Solar

H. C. Hottel and J. B. Howard in their book *New Energy Technology: Some Facts and Assessments*[2] state that until new knowledge is available, studies of large-scale power from the sun via the flat-plate collector are a waste of time and money. Yet in the last year there has been some revival of interest in solar power, largely as the result of some interesting proposals by Drs. Aden B. and Marjorie P. Meinel.[3] The Meinels' ideas are based on the use of films that absorb most of the incident solar radiation but re-emit little infrared radiation. Thus in effect their collectors would be small greenhouses. In one concept proposed by the Meinels, tubes running east-west conduct molten sodium through the collection system. The tubes are enclosed in glass pipes that are evacuated to protect the selective radiation film on the tubes and to suppress heat transfer by convection and conduction. Fresnel lenses focus sunlight onto the tubes. Heat absorbed by the sodium is stored in a large vessel containing a eutectic mixture of salts with a suitable melting point. Heat is extracted from the storage units at 1000 F and used to generate steam, which drives turbogenerators at an efficiency of 41 percent. The Meinels estimate the capital outlay to be around $1000/kw.

We at the Oak Ridge National Laboratory, under a National Science Foundation contract, have briefly examined the idea of using the heat from sunlight to generate electricity. In general, our estimates of the situation are less optimistic than the estimates offered by proponents of the various systems. The storage system seems to present a particular difficulty: for a 1000-MWe plant, 16-hr storage of heat requires about 8×10^8 lb of salt that melts at a reasonable temperature. Moreover, the storage system would have to be even larger if allowance is made for prolonged periods of cloud cover, and heat storage appears completely impractical for smoothing out seasonal variations. Alternatives then might be batteries or generation of hydrogen for short-term storage, and hydrogen probably could even be used for seasonal storage.

We have tried to estimate the cost of such solar systems, but since nothing approaching a full design of a solar-energy power plant has been made, there is no way to obtain an accurate cost estimate for such a plant. However, it can be said that the cost of the converter plant—heat to electricity—will be completely dwarfed by the cost of the collector field and

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[1] Director on leave; presently Visiting University Professor, Vanderbilt University.

[2] M.I.T. Press, Cambridge, Mass., 1971.

Based on a presentation at The Energy Crisis Forum held at the 1972 ASME Winter Annual Meeting.

[3] "Is It Time for a New Look at Solar Energy?" *Bulletin of the Atomic Scientists*, Vol. 27, No. 8, Oct. 1971, pp. 32–37.

approaches for the energy crisis

the storage plant, regardless of the type of storage used. We estimate about \$3000/kw for just the collector field of the first-of-a-kind plant. If we can rationalize and automate manufacture of modules (on-site production of glass, for example), this might be reduced to perhaps \$1100/kw. To this of course must be added the cost of the storage systems, heat-conversion equipment, etc. Thus a very rough estimate would put the cost of a solar plant at not less than \$1100/kw in 1972 dollars. This is \$800 more than for a fossil-fuel plant. At this price the solar plant would be competitive if the cost of fossil fuel rose to around \$1.87 per 10^6 Btu. Thus solar energy appears to be a poor economic bet compared with nuclear energy[6] (which is competitive with fossil fuel at, say, 30¢/10 Btu). Should the breeder be unsuccessful (which seems very unlikely), ordinary water reactors would compete favorably with solar plants even if the price of uranium ore exceeded \$100/lb. At this price, the total cost of electricity from light-water reactors would be less than 2¢/kwh, compared to 2.3¢/kwh from a solar plant that cost \$1100/kw.

Nevertheless, the U. S. should continue work on solar energy, if only to establish with better reliability both its cost and its technical feasibility. We could thereby determine an *upper* limit to the cost of prime energy in the very unlikely event that nuclear energy in the future encounters some unexpected and insurmountable obstacle.

Fusion

Two different approaches to fusion have developed: magnetic confinement and laser-induced microexplosions (so-called inertial confinement). In the case of magnetic confinement, the measure of success is the Lawson criterion: the product *nt* in a D-T plasma must exceed 10^{14} sec/cc and the ion temperature must be around 10 keV. The best that has been achieved in the various tokamaks is $n = 3 \times 10^{13}$, $t \sim 50 \times 10^{-3}$ sec, so that $nt \sim 10^{12}$. We thus need two additional orders of magnitude before the zeroth-order scientific feasibility can be established.

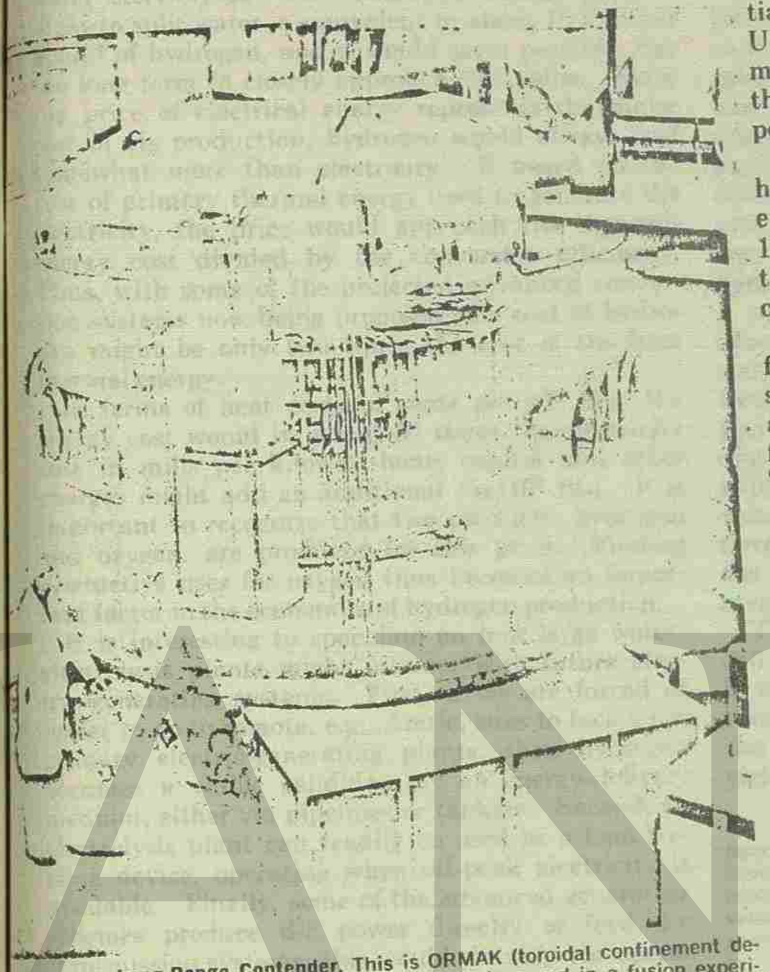
But even when a plasma with $nt > 10^{14}$ has been achieved, there are extremely serious technological problems that remain; the magnetic-field coils are superconducting, the lithium coolant is at ~1832 F, and the distance between these temperature regimes is only 6½ ft. Perhaps the knottiest question is the radiation damage to the inner vacuum wall: will it be necessary to replace the vacuum wall every couple of years because it swells or embrittles under the intensive bombardment of 14-MeV neutrons? And what about the non-negligible after-heat (10 MW in a 5000-MW reactor) and intense radioactivity induced in the walls, or the 100×10^6 curies of tritium in the reactor, or the necessity in D-T to breed tritium from lithium? These are not insoluble problems, but they are obviously tedious and tricky and it would be wrong to count on technical feasibility being demonstrated on any specific timetable.

The laser-induced microexplosions are a recent development about which little has been said publicly. Here small pellets of D-T ice are imploded by converging laser beams. The resulting microthermonuclear explosions are contained in a stout pressure vessel. One ingenious idea is to line the vessel with a swirling layer of liquid lithium that is filled with gas bubbles to increase its ability to absorb the microshocks.

Obviously there are difficulties: to get lasers with high enough power, to control the pellet dispenser, to absorb energy. For a practical power reactor, the laser energy that must be delivered in a fraction of a nanosecond exceeds 10^5 joules. The largest laser available today delivers 600 joules in 2 nanosec. But there is a fair enthusiasm for these methods, and it would be wrong to discount this possibility. By like token, this is a long-shot scheme that may or may not prove practical at some unspecified future date.

Geothermal

Here we are talking not about an inexhaustible energy source, but about one that is now in use and whose full potential has not yet been developed. As with the other systems, one can identify optimists and pessimists. Perhaps because of the impressive credentials of the most optimistic of the geothermal enthusiasts, Prof. Robert Rex of the University of



Long-Range Contender. This is ORMAK (toroidal confinement device) in double exposure, a device being used in a fusion experiment that examines the confinement and heating of plasmas intended for fusion power reactors. The composite photograph shows the final assembly of ORMAK, including the completed iron core in the foreground and the frame holding the laser optics in the background. The large ports at center elevation (on left and right) of the tank are for future use with high-current injectors. Construction was completed in January, 1971.

California at Riverside, this writer tilts toward the optimists. At the 1972 Cornell workshop on energy sources,[4] Professor Rex pointed out three possibilities: dry steam, hot water, and hot rock. Dry steam now supplies 192 MW of electricity in northern California at competitive prices. Professor Rex estimates this resource in that part of California at 25,000 MW (although others claim this estimate may be high by a factor of five), and it is not unlikely that other dry-steam fields will be found elsewhere in the west.

Hot-water systems are estimated to be about 20 times as numerous as dry-steam systems and also may be of larger size. Over a thousand have been identified in the U. S. on the basis of hot springs. One of the large ones occurs in the Imperial Valley of California, where Rex estimates the power potential is 30,000 MW. The total power potential in the U. S. from this source is not known, but it is estimated to be between 10^6 and 10^7 MW. The life of the resource is also unknown, but studies in the Imperial Valley suggest this to be 100 to 300 years.

The largest potential for geothermal energy is in hot rock. According to calculations by Rex, the present recoverable reserve in the west is of the order of 10^8 MW-centuries; thus if hot rock can be used for thermal power, most of the U. S. demand for energy could be satisfied thereby.

The big question is, just how feasible is hot rock for power production? Rex proposes the following scheme: Two wells are drilled a few hundred feet apart. The input well might be from 8000 to 20,000 ft deep to reach temperatures of 338 F to 572 F. The output well is perhaps 3000 ft less deep. Hydraulic fracture is used to establish cracks between the wells. Cold, dense water flows down the deeper well and rises convectively through the crack system. The rock loses heat to the water, which expands slightly and rises through the shallower well to the surface. This hot water flows through a heat exchanger on the surface to drive a low-boiling working fluid through a turbine. Rex estimates power costs at around 15 mill/kwh for this system.

This idea is elegant in concept, yet we really don't know whether it can be made to work. Would water injected into the one well come out the other, or would it be forever lost in the bowels of the earth? Would the water that comes up be so laden with crud as to make the whole thing an engineering nightmare? Experimental testing is now underway at Los Alamos, Livermore, and Pacific Northwest to determine how these difficult geological questions can be resolved.

Hydrogen

It seems clear that ultimately mankind will have two energy systems: a primary one depending on either fission, fusion, or solar sources and a secondary system that will take care of portable energy needs. To a growing band of dedicated "hydrogenophiles," this secondary source will be H_2.

The great advantage of H_2 is that it is essentially nonpolluting; if it is burned catalytically at low temperature, its combustion leads only to H_2O. Even when hydrogen is burned with air in conventional internal-combustion engines, H_2 can be controlled to meet the 1975–1976 Environmental Protection Agency standards, including that for NO_x. Further, in nearly all applications hydrogen appears to be capable of substituting for today's fossil fuels. Practical questions then remain: Can widespread use of H_2 be safe? Can H_2 be manufactured, ultimately from water and prime energy, at anything approaching reasonable costs?

Methods of H_2 manufacture—sunlight and biological, heat and enzymes, electrolytic, chemical—should be discussed, if only briefly. The most probable large-scale production process would seem to be

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[4] "Summary Report of the Cornell Workshop on Energy and the Environment," sponsored by the National Science Foundation, Committee on Interior and Insular Affairs, U. S. Government Printing Office, Washington, D. C., 1972.

water electrolysis. The theoretical energy requirement to split water is equivalent to about 15 kwh per pound of hydrogen, and it would seem possible over the long term to closely approach this value. Since the price of electrical energy represents the major cost of H_2 production, hydrogen would always cost somewhat more than electricity. If based on the cost of primary thermal energy used to generate the electricity, the price would approach the thermal-energy cost divided by the conversion efficiency. Thus, with some of the projected advanced conversion systems now being proposed, the cost of hydrogen might be only two times the cost of the base thermal energy.

In terms of heat costs in cents per 10^6 Btu, the energy cost would be about 30 times the electricity cost in mills per kilowatt-hour; capital and other charges might add an additional 45¢/10^6 Btu. It is important to recognize that two products, hydrogen and oxygen, are produced for this price. Finding productive uses for oxygen thus becomes an important factor in the economics of hydrogen production.

It is interesting to speculate on how large water-electrolysis plants might interact with future electric-generating systems. First, if we are forced or prefer to go to remote, e.g., Arctic, sites to locate our primary electric-generating plants, then hydrogen becomes a viable candidate as an energy-delivery medium, either via pipelines or tankers. Second, an electrolysis plant can readily be used as a load-leveling device, operating when off-peak electricity is available. Finally, some of the advanced generating schemes produce d-c power directly or feed d-c transmission systems; this would simplify the operation of an electrolysis plant, which requires large quantities of d-c power. Also, the deuterium required in fusion reactors could be produced as a by-product of water electrolysis.

Processes for hydrogen (and oxygen) production that require only thermal energy are now under active development by Euratom in Europe. These processes use a closed set of four or more chemical reactions so that, with inputs of only heat and water, hydrogen and oxygen are produced; all the reaction products are internally recycled. Similar ideas were intensively studied in this country a few years ago and are currently receiving renewed attention at several laboratories. These production systems seem to be some distance from commercial practice, but if developed they would have the inherent advantage of not first requiring the conversion of thermal to electrical energy for hydrogen production. One must remember, however, that such systems are not without certain inefficiencies, so it is not now clear how these systems may ultimately compare with other methods of production.

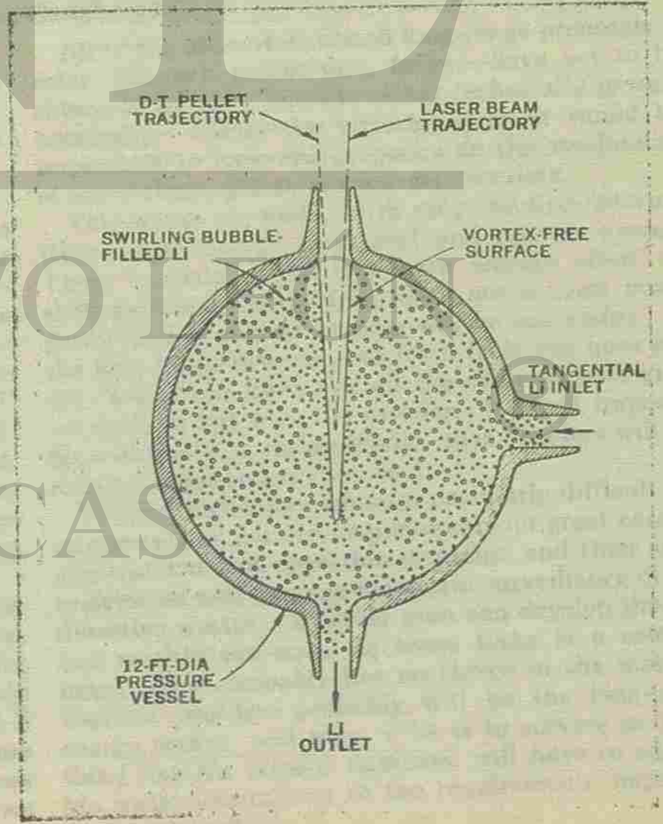
Other Intriguing Possibilities

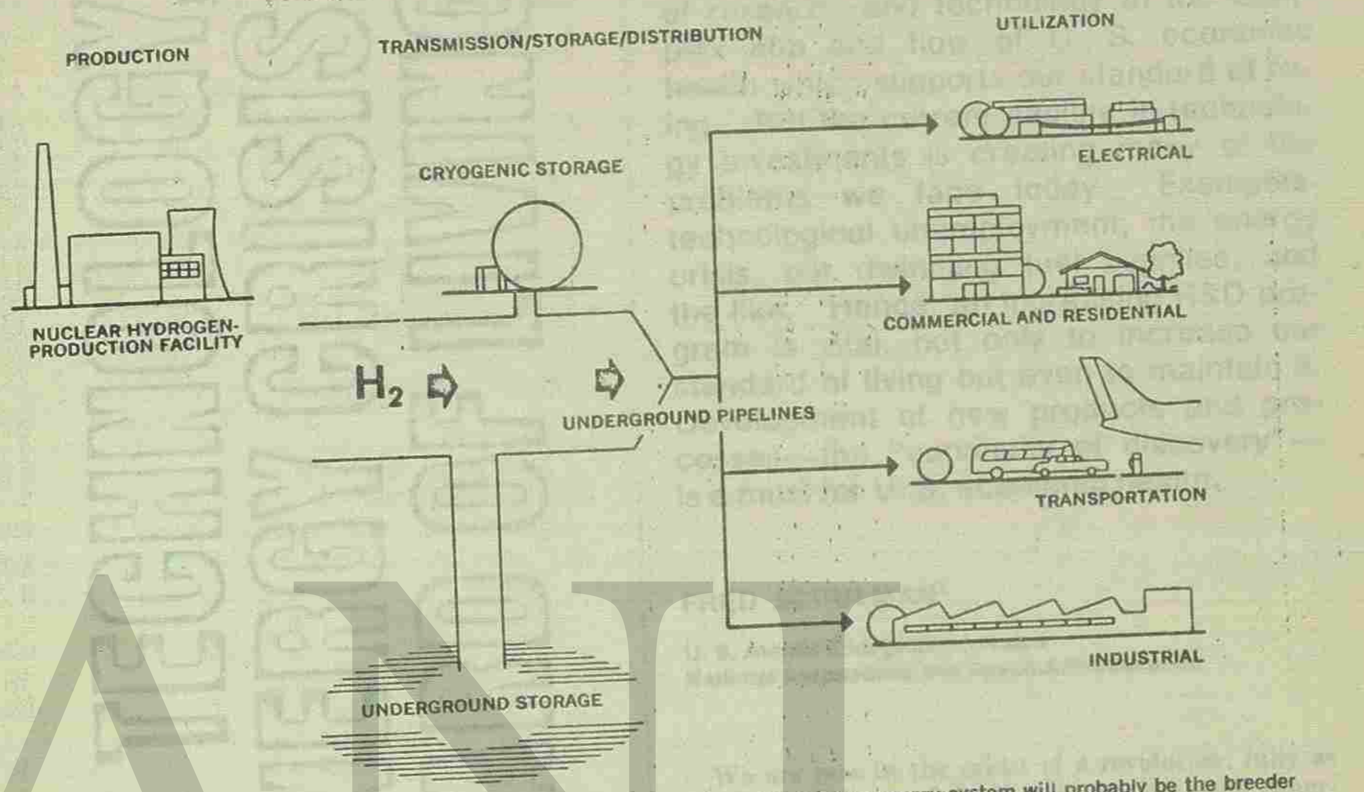
There are some further intriguing production possibilities just now being considered that involve basically biological processes.

It is possible to use photosynthetic organisms in a photochemical fuel cell. Plants and blue-green algae can utilize water as a reductant in light-dependent generation of compounds (such as reduced ferredoxin and viologens) that are equivalent to molecular hydrogen as reductants. In addition, in the living organism, the ferredoxin and ATP are then used to reduce carbon dioxide to cell material. However, the production of cell material is not a necessary step in the harnessing of light energy. Energy storage as hydrogen would be more efficient and direct. Such a conversion could be accomplished if the photochemically reduced reductants (ferredoxin, etc.) were coupled to a hydrogenase. Essentially this process would represent a photolysis rather than an electrolysis of water. The requirements for such an aqueous system would be: light, a stabilized photochemical apparatus capable of generating reductants from water, ferredoxin or a similar electron carrier, and a ferredoxin-coupled hydrogenase. Stabilization of the photochemical apparatus is the critical requirement of this system.

The efficiency of the proposed photosynthetic fuel cell appears to be sufficiently high to be economically useful. Under laboratory conditions, energy-conversion yields of up to 10 percent are encountered in the isolated photosynthetic apparatus. If such yields can be obtained with a stabilized photochemi-

Conceptual design of a fusion reactor that makes use of the fusion reactions occurring when an intense laser beam heats the deuterium–tritium ice pellet within the center of a spherical reactor vessel filled with molten lithium.





Hydrogen Energy System. The hydrogen system is actually a secondary system; the primary energy system will probably be the breeder reactor.

cal system, one readily calculates that of the 0.8 cal/cm^2/min of solar energy that strikes the earth's surface every day, the total yield of the proposed photosynthetic fuel cell would be some 500 kcal/m^2/day. A 500-ton/day hydrogen-production plant would require an area of 14,000 acres or about 22 sq mi.

What about the safety of widespread use of hydrogen? Most fuels require some care and control, so that fuel substitution becomes a matter of degree or extent of control required. Gas containing 50 percent hydrogen was distributed to urban homes for many years as town or coal gas. Safety problems encountered often stemmed from the non-hydrogen component, carbon monoxide. NASA and the AEC are routinely handling liquid hydrogen in large volume and have compiled an impressive safety record. Hydrogen is extensively pipelined in and around refineries and transported daily as either liquid or gas over our highways and railways—also with excellent safety records.

Some of the basic properties of hydrogen that relate to safety are that its lower explosive limit is similar to that of natural gas (~5 percent), its explosive or ignition energy is relatively low, and its diffusivity is relatively high while its volumetric heat content is one-third that of natural gas. While it will require some care and respect in handling, hydrogen does not appear to be fundamentally more dangerous than many other fuels we use daily.

Conclusions

All of the above-mentioned long-range proposals—solar, hot-rock geothermal, fusion—have yet to be shown to be fully feasible either technically or economically. Under the circumstances, it would be imprudent to base energy policy on the availability of any of these options at some definite time.

This leaves us, really, with only two firm alternatives—clean energy from coal and nuclear energy. There is little doubt that with enough effort we shall get clean energy from coal, nor is there much doubt that a nuclear breeder will be successful. In the long term, however, our fossil fuels will have run out, and if one discounts all the other technologies, we shall be left with the breeder. It is not impossible—in fact it is rather likely—that breeders will be man's ultimate energy source.

Nuclear technology imposes peculiarly difficult requirements on society, requirements for great care in construction and operation of plants and their subsystems as well as some long-term surveillance of radioactive wastes. Whether man can develop the social institutions equal to these tasks is a central issue. Man probably has no choice in the matter. Nuclear breeders probably will be the long-term energy source, and man, if he is to survive in anything like his present numbers, will have to adjust his social institutions to the requirements imposed by this technology.

TECHNOLOGY, THE ENERGY CRISIS, AND OUR STANDARD OF LIVING

Here's a picture of the dynamic position of research and technology in the complex ebb and flow of U. S. economic health which supports our standard of living. But the current decline in technology investments is creating many of the problems we face today. Examples: technological unemployment, the energy crisis, our dwindling fuel supplies, and the like. Hence, an increasing R&D program is vital, not only to increase our standard of living but even to maintain it. Development of new products and processes—the "continuity of discovery"—is a must for U. S. economic health.

FRED SCHULMAN[1]

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We are now in the midst of a revolution, fully as far reaching in our daily lives as was the great American Political Revolution of the 18th Century and Industrial Revolution of the 19th Century. This 20th Century revolution is the Scientific Revolution. Because we are in the midst of this revolution, we are not often able to see where it is taking us, but that it is enriching our lives as well as posing problems common to all revolutions, such as rapid change, is obvious. Competing for primacy and threatening to supplant it are the major subdivisions now gaining attention such as the energy revolution and the social revolution, with the outcome still in doubt.

U. S. R&D Declining

The United States was and may still be the leading technological society of our day. It still enjoys the highest per capita standard of living in the world. Cheap energy does most of our work and sustains our transportation system. Our rate of technology investment has continuously increased during this century until 1965, when for the first time the rate of investment in research and development began to decline and is still declining. We sometimes forget that there is a definite relationship between standard of living and productive investment. Thus, Prof. Edward Shapiro of the University of Detroit has written that without technological innovation, investment will languish and without the

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Based on an address presented on Engineers and Architects Day—1973, Arlington, Va.

necessary rate of investment, our private enterprise economy will stagnate. According to the United Nations, the five countries with the highest per capital GNP in 1970 were the United States, Kuwait, Sweden, Canada, and Switzerland, with per capita incomes ranging from $3,670 in the United States to $2,310 in Switzerland. All of these countries have enjoyed considerable research and development with the exception of Kuwait which does, however, enjoy a fantastic oil income and investment. It might be interesting to note that Kuwait consumes even more energy per capita than does the U. S., its consumption amounting to 11,905 kg coal equivalent per capita to 10,331 kg for the U. S. The countries with the lowest per capita national product are Burundi, Somalia, Upper Volta, and Ethiopia with per capita GNP of only $50 to $60 per year.

It is interesting to note that since 1910 the population of this country has increased 122 percent, while the real gross national product has increased 600 percent so that living standards have risen steadily despite the huge increase in population. The per capita income during this period rose from approximately $1200 to $3500 per year. But, and this is the important point, we are currently on a plateau, and there is no real growth in per capita national product. If there is no growth in the national product per person, how are we going to pay for better schools and better health and social needs? How are we going to provide the energy needed to make the U. S. comfortable and productive from fast-dwindling cheap energy sources without a high order of new technology? This decline in technology investment in the United States which commenced in 1965 may well have been the start of most of the problems facing us today. Since the United States enjoys high wages, it obviously requires jobs which can produce sufficient real wealth to support those wages. Furthermore, new industries must be created to absorb the approximately one million new workers who enter the labor force each year.

How can we do this without discovering new products and processes which are the direct result of research and development? How will nuclear breeders and fusion or solar energy progress from promise to fact? The answer is more research and development—*not less.*

Technology and the Dollar

But how does technology relate to the more direct everyday concerns of living standards. The dollar is under severe pressure from abroad. Inflation is very difficult to reduce. Advanced technology can help to solve both these problems.

Since 1964, net exports of U. S. goods and services have fallen from a surplus of $8.5 billion to the first deficit of the century last year, as shown in Fig. 1. Furthermore, the largest American exports, except for food, have been principally the high technology products of research and development such as elec-

Fig. 1 U. S. Foreign trade.

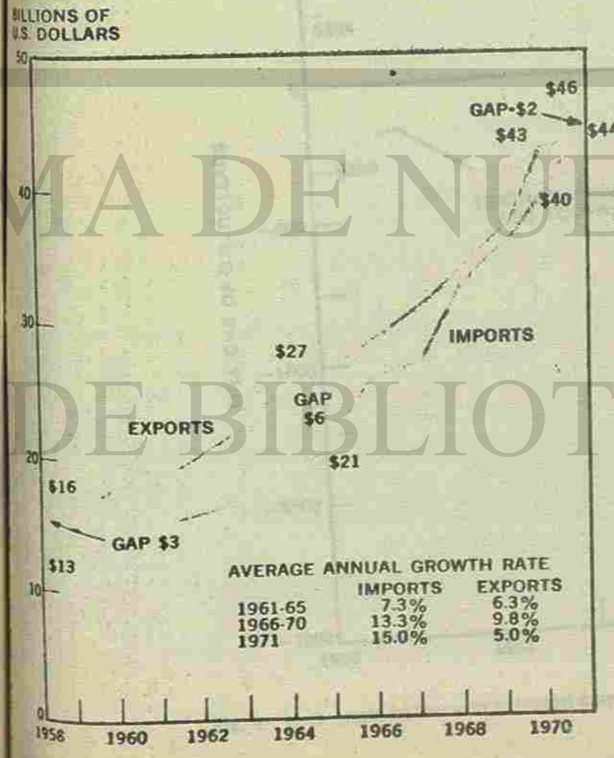
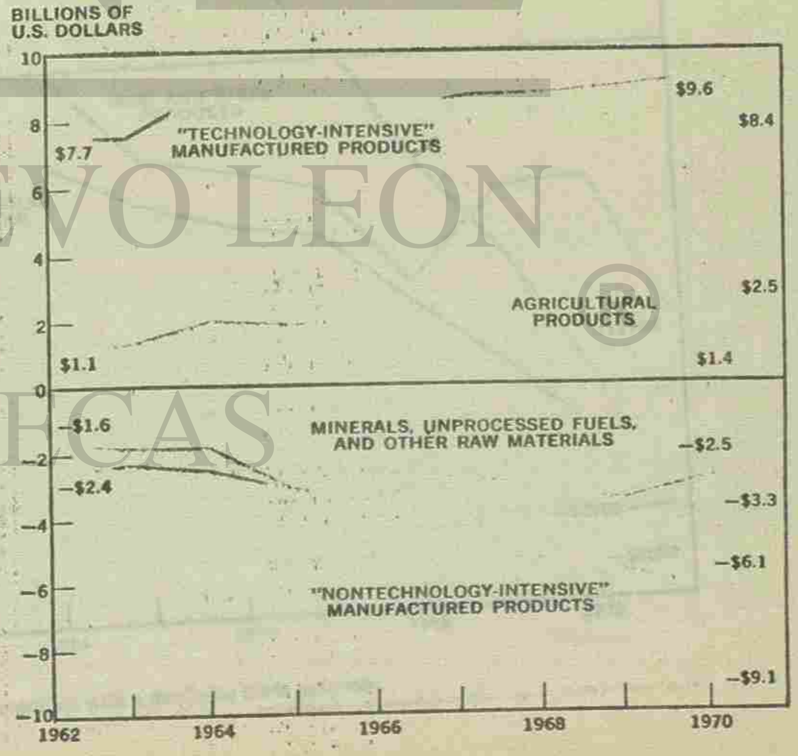


Fig. 2 U. S. trade balance trends.



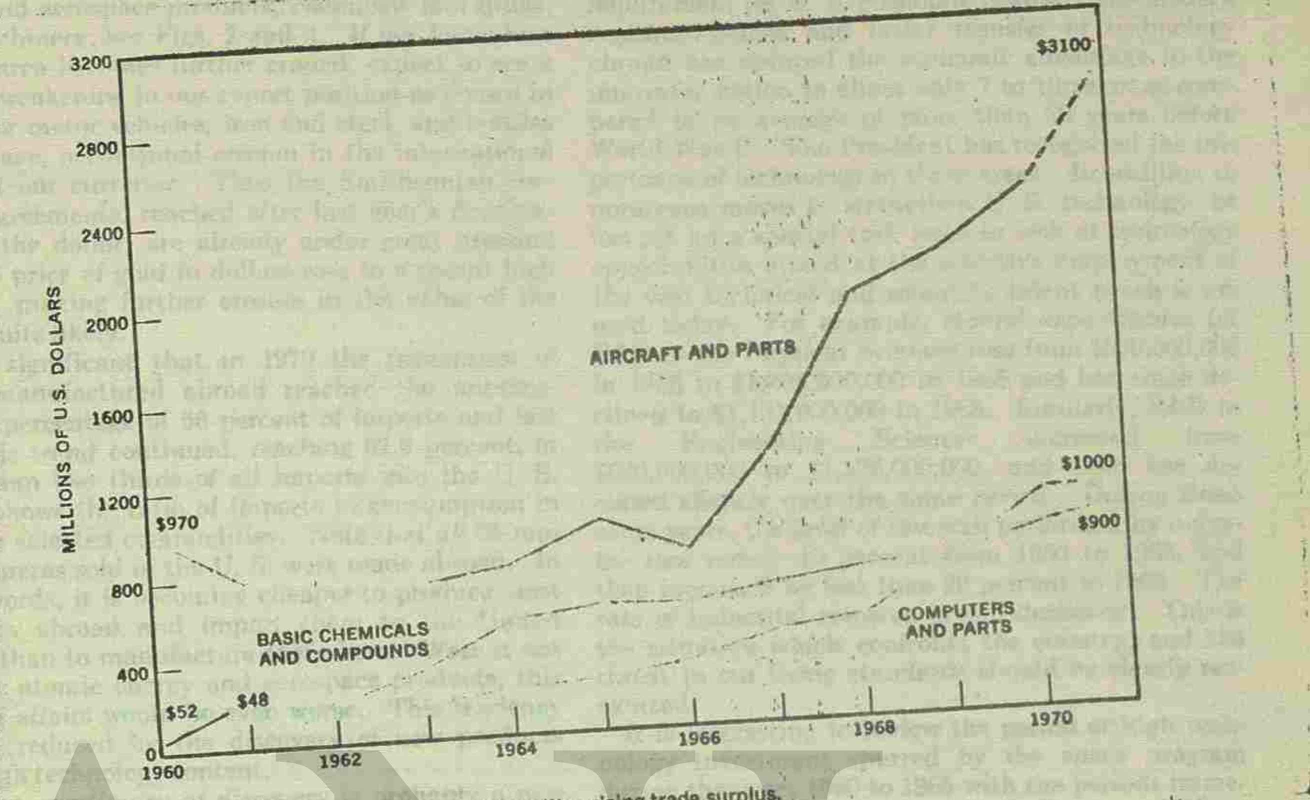


Fig. 3 U. S. trade balance in selected commodities with a rising trade surplus.

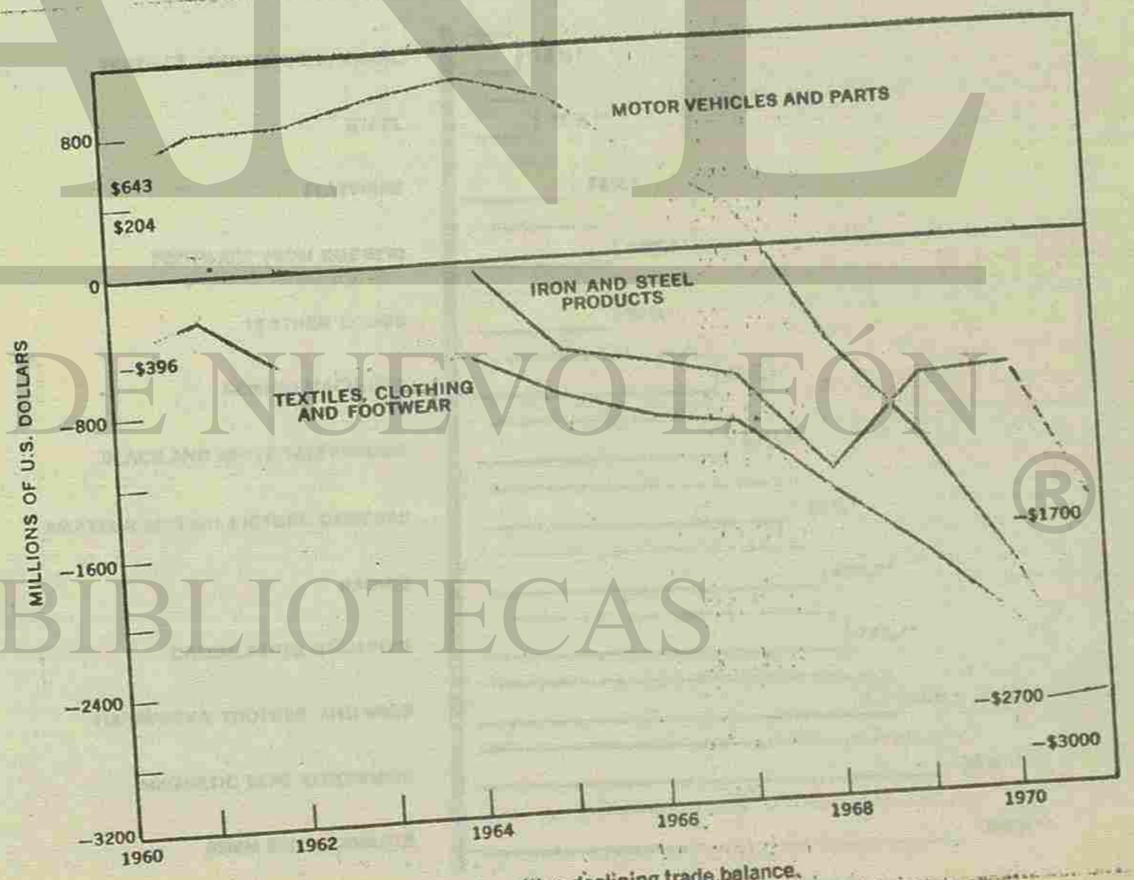


Fig. 4 U. S. trade balance in selected commodities with a declining trade balance.

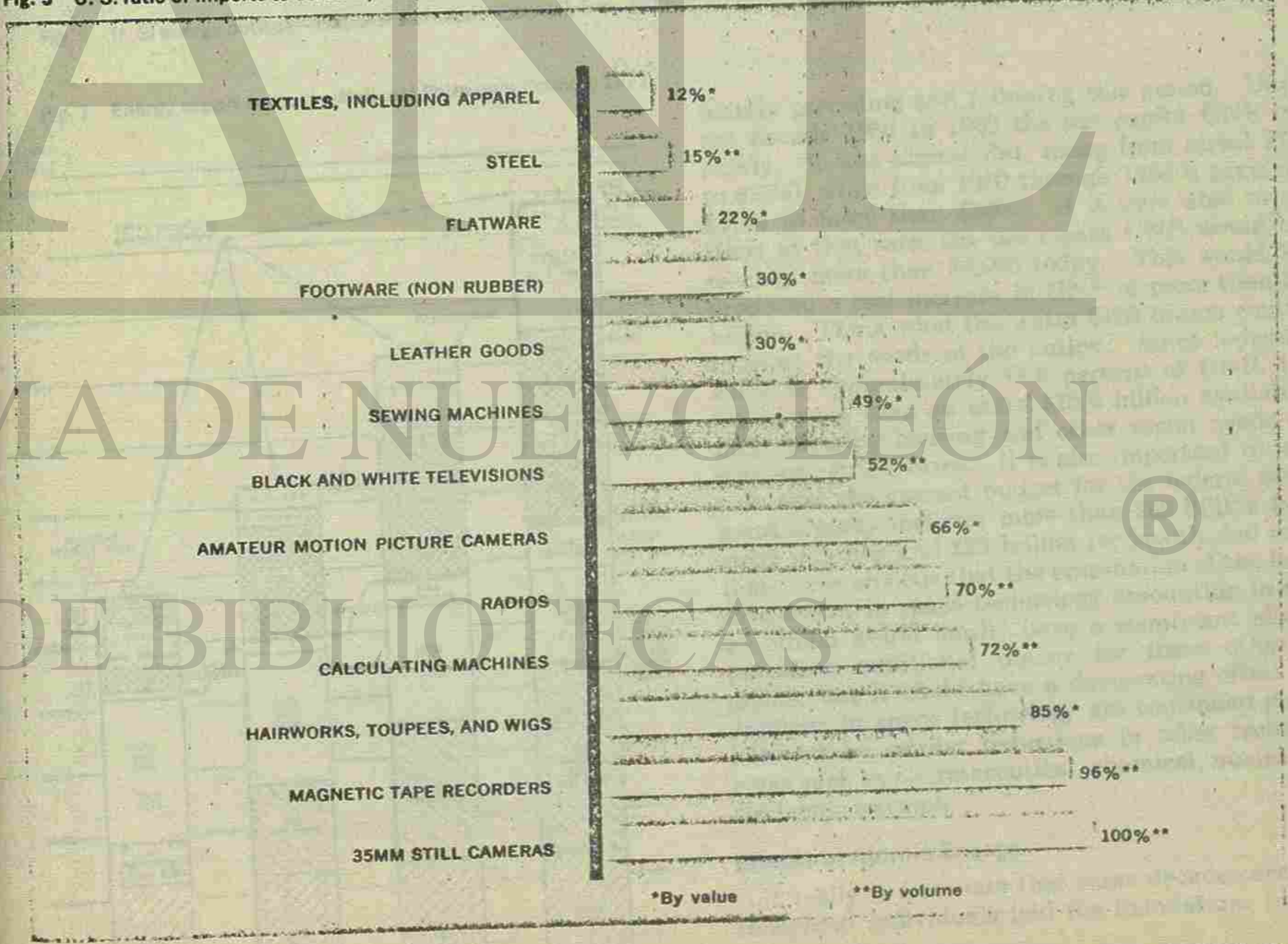
tronic and aerospace products, chemicals and drugs, and machinery; see Figs. 2 and 3. If our know-how in this area becomes further eroded, expect to see a further weakening in our export position as shown in Fig. 4 for motor vehicles, iron and steel, and textiles and, hence, a continual erosion in the international value of our currency. Thus the Smithsonian currency agreements, reached after last year's devaluation of the dollar, are already under great pressure and the price of gold in dollars rose to a recent high of $128, making further erosion in the value of the dollar quite likely.

It is significant that in 1970 the percentage of goods manufactured abroad reached the unprecedented percentage of 56 percent of imports and last year this trend continued, reaching 67.6 percent, or more than two thirds of all imports into the U. S. Fig. 5 shows the ratio of imports to consumption in 1970 for selected commodities. Note that *all* 35-mm still cameras sold in the U. S. were made abroad. In other words, it is becoming cheaper to produce most products abroad and import them to the United States than to manufacture them here. Were it not for new atomic energy and aerospace products, this state of affairs would be even worse. This tendency can be reduced by the discovery of new products with high technology content.

In fact, *continuity of discovery* is probably a new requirement for U. S. economic health, since modern communications and faster transfer of technology abroad has reduced the economic advantage to the innovator nation to about only 7 to 10 years as compared to an average of more than 30 years before World War II. The President has recognized the importance of technology in these areas. In addition to numerous moves to strengthen U. S. technology, he has set up a special task force to look at technology opportunities aimed at the effective employment of the vast technical and scientific talent which is unused today. For example, federal expenditures for R&D in the Physical Sciences rose from $600,000,000 in 1960 to $1,705,000,000 in 1965 and has since declined to $1,131,000,000 in 1968. Similarly, R&D in the Engineering Sciences increased from $690,000,000 to $1,576,000,000, and then has declined slightly over the same period. During those same years, the level of research performed by industry rose nearly 40 percent from 1960 to 1965, and then increased by less than 20 percent to 1968. The rate of industrial research is still declining. This is the situation which confronts the country, and the threat to our living standards should be clearly recognized.

It is interesting to review the period of high technology investment spurred by the space program during the years 1960 to 1965 with the periods imme-

Fig. 5 U. S. ratio of imports to consumption, 1970.

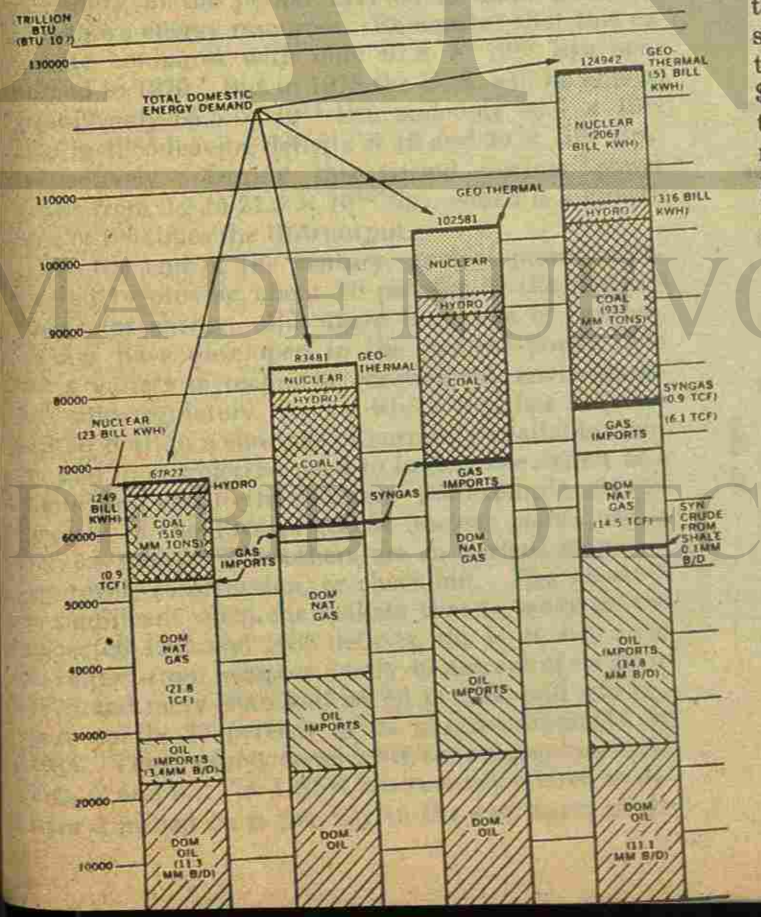


	1970	1975	1980	1985
Total domestic energy consumption	67,827	83,481	102,581	124,942
Total projected domestic supply				
Oil	21,048	22,789	24,323	23,405
Gas	22,388	20,430	18,030	14,960
Coal	13,062	15,554	18,284	21,388
Hydropower	2,677	2,840	3,033	3,118
Nuclear	240	3,340	9,490	21,500
Geothermal	7	120	343	514
Synthetic oil	—	—	—	197
Synthetic gas	—	380	570	940
Total domestic supply	59,422	65,453	74,073	86,022
Shortage indicated	8,405	18,028	28,508	38,920
Projected imports and other Means for supplying fuels to make up for shortage				
Imported oil	7,455	15,284	22,163	29,997
Imported gas	950	1,610	3,880	6,280
Additional coal production	—	756	1,643	1,762
Additional residual fuel imports	—	378	822	881
Total	8,405	18,028	28,508	38,920

Figure units in 10^{12} BTU

Fig. 6 U. S. energy outlook—National Petroleum Council, Nov. 1971.

Fig. 7 Energy supply sources—National Petroleum Council, 1971.



diately preceding and following this period. During the decade 1950 to 1960 the per capita GNP grew slowly. It was almost flat, rising from about $2500 to $2700, while from 1960 through 1966 it grew from $2700 to more than $3400. If it were able to continue at that rate, the per capita GNP would have reached more than $4,000 today. This would have produced a real increase in GNP of more than $100 billion. Think what this extra $100 billion could do to meet the needs of the nation. Since federal income is approximately 18.6 percent of GNP, there would have been an extra $18.6 billion available to meet pressing housing and other social needs even without raising taxes. It is also important to recognize that the current budget for the federal government already includes more than $60 billion for income security and $25 billion for health and education. It is obvious that the elimination of the federal investment in space technology amounting to about $3 billion would hardly have a significant effect in providing additional money for these other programs, but it could have a devastating effect if reductions in space technology are continued and are followed by similar reductions in other technology areas such as pharmaceutical, chemical, nuclear, and electronic research.

Effects of Atomic Energy

It really is fortunate that some decades ago a few farsighted individuals laid the foundations for what is now the atomic power industry. It is the power from nuclear energy which almost alone can sustain the American standard of living for the forseeable future under conditions as they are emerging both here and abroad. It is important to realize that total energy consumption increased by 50 percent in the decade 1960–70 (from 44.6 to 67.8 quadrillion Btu's). Total future U. S. energy requirements have been estimated by the National Petroleum Council as 83.5 × 10^{15} Btu in 1975, growing at 4.5 percent per year at 125 × 10^{15} Btu in 1985. This is shown in Fig. 6.

The energy crisis may perhaps be put in perspective by the following findings made by the 1971 report to the Secretary of Interior by his advisory National Petroleum Council: These are shown in Fig. 7.

1 NPC estimates U. S. energy consumption growth at 4.2 percent annually during 1971–85 with electric utility consumption rising at 6.7 percent per year. This is roughly 4 to 7 times the population growth estimated by the Bureau of the Census.

2 Oil imports will rise to 57 percent of oil consumption and 25 percent of total energy use in 1985.

3 Natural gas imports which now amount to 4 percent of gas supplies will rise to more than 28 percent in 1985.

4 Coal production will rise to 1,071 million tons in 1985 from 590 million tons in 1970 if SO_2 can be commercially controlled.

5 Nuclear power will rise from 23 billion kwh in 1970 to 2,068 billion kwh in 1985 or about 48 percent of electricity supply.

6 Energy sources other than oil, gas, coal, and nuclear will not exceed 3 percent of need by 1985.

7 Huge capital costs of about $375 billion will be necessary in the period 1971–85 to make available the above energy resources. Remember that this estimate compares with only 67.8 × 10^{15} Btu consumed in 1970. But in 1975 the U. S. will be able to supply only 65.5 × 10^{15} Btu and only 86.0 × 10^{15} Btu in 1985 leaving deficits of 18 and 39 × 10^{15} Btu, respectively. During this period nuclear power grows from 0.2 to 21.5 × 10^{15} Btu, which is a growth rate of 100 times the 1970 output.

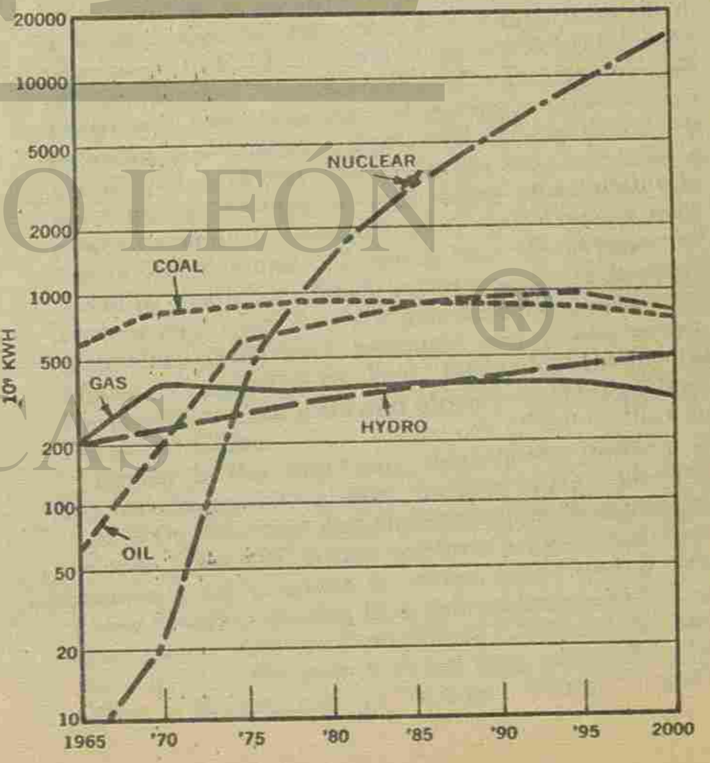
By the end of the century, nuclear power is expected to provide about 50 percent of the nation's needs for energy. But there is a note of caution. Delays have developed in the nuclear power field for a variety of technical, mechanical, environmental, and regulatory reasons which together have resulted both in a shortage of currently available energy and in a projected need to import the deficit at a significant cost to the country. For example, only 25 percent of the 1972 projected nuclear plants are in service today. The others are in various stages of approval, construction, or check-out. The shortfall is significant when one realizes that to make up the expected 1975 and 1985 deficits, the U. S. will have to import from overseas nearly 40 percent of its oil in 1975 and more than half its oil in 1985 and will import nearly 30 percent of its gas requirements by 1985. These supply sources are shown graphically in Figs. 7 and 8. The USSR has recently offered to deliver 2 billion cu ft per day to the east coast of the U. S. Soviet gas reserves have been estimated by academician V. S. Emelyanov as 1,860 billion cu m. But, an investment amounting to billions of U. S. dollars in Russia will be needed to produce and ship this gas even if reliability of the Russian source is assumed.

Nuclear plant delays have an immediate cost impact to the consumers affected. For example, the Wisconsin Public Service Commission was recently requested to approve a 5.7 percent rate increase to compensate the utility for increased electric energy costs due to one to two years delay in approval and construction of two nuclear power plants, and the three-year delay in availability of Indian Point 2 is increasing costs to a similar, equivalent, rate increase.

Obviously, nuclear technology is an important, though often misunderstood, factor in both the near-term and long-term solution to energy, unemployment, and balance of trade problems. First; by selling nuclear fuel services and reactors abroad, it is contributing to strengthening the value of the dollar by reducing the balance of payments deficit. Second; by providing electrical and process energy, it is reducing the need for foreign oil, with all the attendant political, diplomatic, and financial strains which such reliance implies. Third; by helping to maintain an adequate supply of energy in this country, brownouts, black-outs, and shutdown of industry can be avoided.

Gerard C. Gambs, Mem. ASME, Vice-President,

Fig. 8 Forecast of generation of electricity in U.S. by types of fuel.



Ford, Bacon, David Inc. of New York, has estimated that a delay of only 10,000 MWe requires the importation of 100,000,000 bbl per yr of oil. Since, Mr. Gambs does not believe it feasible to import the huge amounts of oil and gas that may be needed, he forsees a cessation of industrial plant expansion and rationing of fuels. The difficulty of importing such fuels can be seen from the President's Economic Report of January, 1972, in which a balance of payments deficit of $23.4 billion was recorded for 1971. Fuel imports can easily double this deficit before 1985, according to Deputy Assistant Secretary of Commerce Stanley Nehmer. However, economists will surely propose measures to prevent this from happening. Such measures are bound to have considerable effect on the lives of all of us. For example, in order to provide the energy expected to be used in this country in 1985, just 12 years away, at least 350 huge supertankers of a quarter million deadweight tons each, would have to be built during 1971–85 to carry the 14.8 million bbl of oil per day to the U. S. even if we could pay for it. Of course, huge new seaports and terminals would have to be built to accomodate these ships in an ecologically satisfactory manner.

We also would need to build new oil refining capacity of 2½ times the rate of the last decade if we are to reach the 10 million bbl per day new capacity required in 1985 and we are already behind schedule. Such delays will result in gasoline shortages which will reach the man in the street in the form of higher gasoline prices, restrictions on use, or both. Furthermore we would need to build 120 liquid-natural-gas tankers, each of 790,000 bbl capacity in the period 1971–85 to haul the 4 billion cu ft of liquified natural gas that must be imported in 1985 to supplement dwindling domestic supplies. Large liquefaction, storage, and gasification plants will obviously be needed to handle this large amount of liquified natural gas.

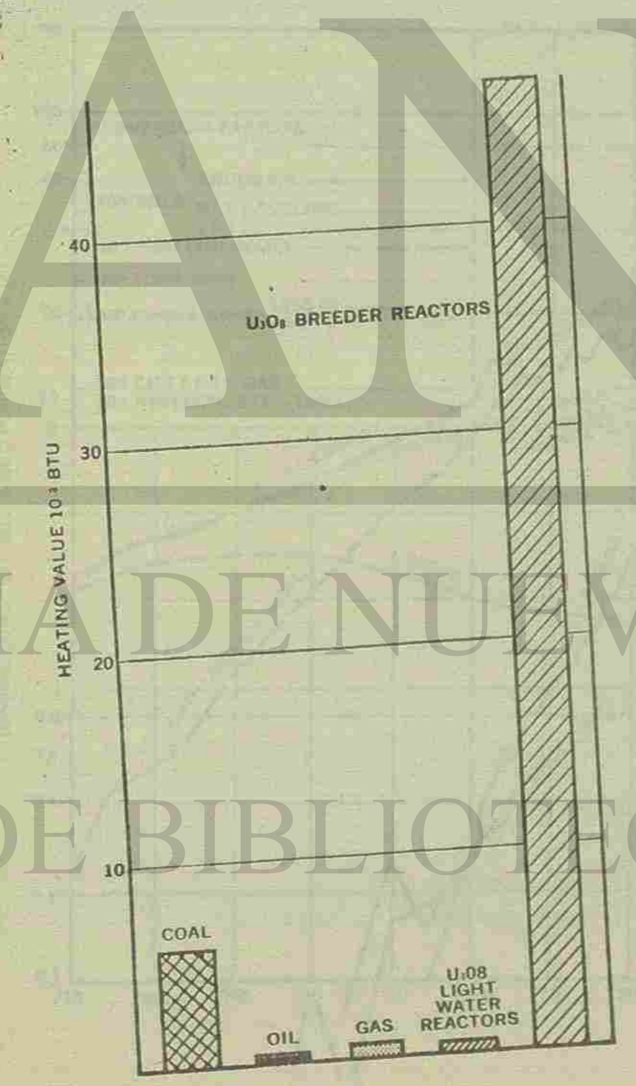


Fig. 9 Nuclear power, breeder reactors in particular, may prove to be a great energy assist in the years ahead.

With the help of Technology

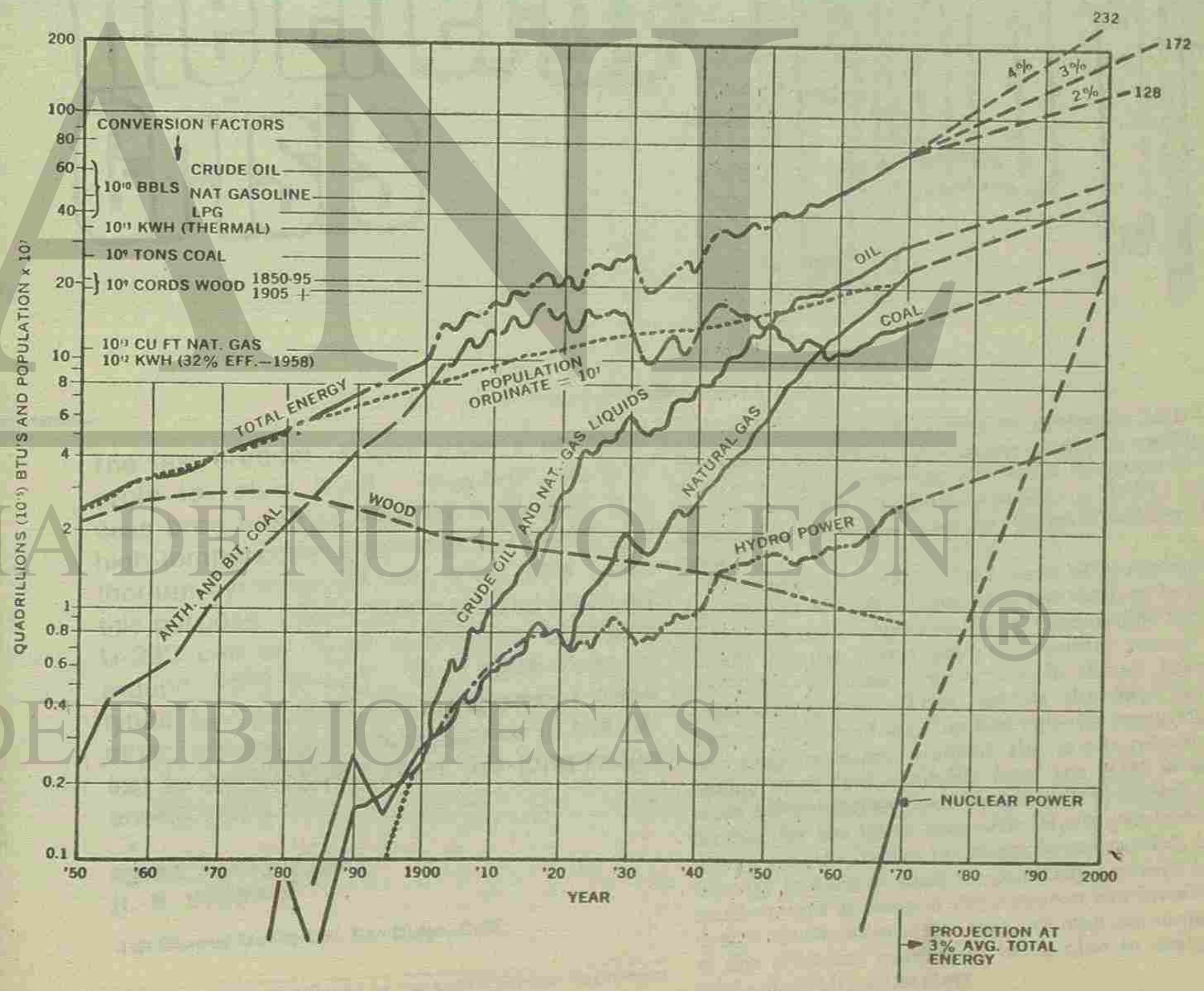
How can technology help? In the nuclear technology area, efficiency in energy use and generation from fission reactors can assist in the immediate years ahead. Beyond this, there is the prospect of breeder reactors multiplying nuclear fuel reserves at reasonable prices (Z $15 U_3O_8) by more than a factor of 100 (to 33.6Q) as seen in Fig. 9. Note that Mr. Gambs raises this estimate to more than 45Q. These are estimates of proved reserves. The figures for coal drops to 0.3Q if we are talking about low sulfur coal and are raised to about 77Q if we want to use the current total estimated but unproved resources of coal. Incidentally, there is currently no economical and practical method of reducing the sulfur content of plentiful high sulfur coal and this is a fruitful area of research. For comparison 1Q is equivalent to 173 billion bbl of oil or 970 billion cu ft of natural gas. Geothermal and solar sources can contribute large amounts of energy if the needed technology is created. Fuel cells of high efficiency (~ 60 percent) and low pollution may serve as a good energy storage system using excess nuclear power capacity for electrolysis of water during periods of low demand. There is also the prospect of doubling available natural gas reserves by controlled nuclear explosions in tight gas formations when the technology finds both technical and public acceptance, as suggested by Prof. Edward Teller of the University of California and already implemented by the Soviet Union.

Finally in the long term, there is the prospect of nuclear fusion with almost limitless energy possibilities, if the scientific and engineering problems can be solved. The AEC fusion research program has been making good progress in recent years and a five-phase program leading to a demonstration fusion reactor power plant of from 500 to 2,000 mw continuous output in the year 2000 has been outlined by the Office of Science and Technology. The U. S. social goal of a continuing rise in the standard of living for more and more of its citizens, including winning the war on poverty, will require an increase in the per capita consumption of energy and so will attempts to improve the quality of life through environmental control. It has been estimated that these two goals alone can add 66 percent to the current per capita energy consumption (Chase National Bank). Fig. 10 shows the historical use and sources of energy in the U. S. since 1850 and projects future energy needs for the American standard of living. The precarious nature of our energy resources is clearly indicated. Note the role projected for nuclear energy. With confidence in the future and hope that the current environmental, technical, and economic problems can be solved, American utilities in 1972 ordered a record 39 nuclear electric generating power plants totalling 42,000 mw. If we are to provide the technology for future energy sources and thus help to provide a decent standard of living in the future for more and more of our citizens, it is important that the current downward trend in real national investment in research and technology be reversed. Fortunately, there are signs that this indeed will occur.

Acknowledgements

The data used in this article are derived from the President's Economic Reports of 1971 and 1972; Statistical Abstracts of the United States for 1970 and 1972; material presented at the Federal Executive Institute, the ASME Forum on the Energy Crisis, Nov. 1972; and other sources.

Fig. 10. U. S. energy consumption by fuels since 1850.



the role of HTGRs and FBRs in meeting the Energy Crisis

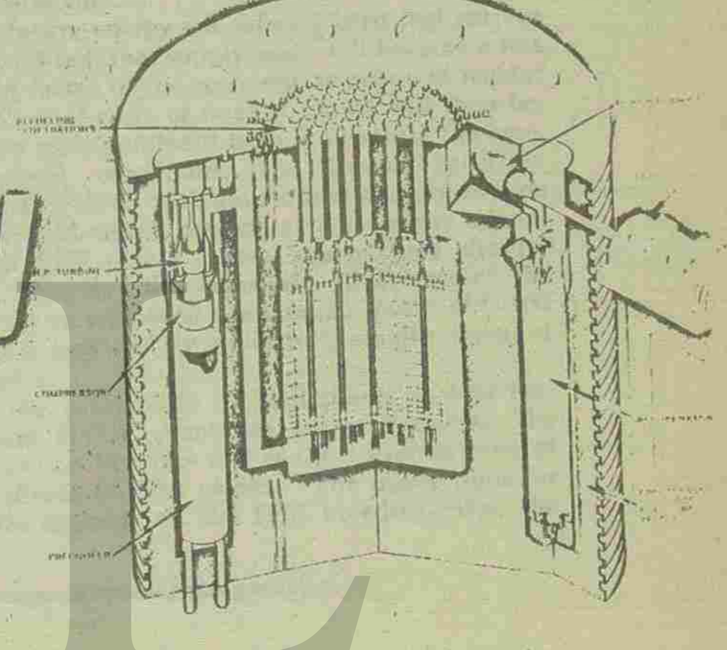


Fig. A 1900 Mw(e) gas turbine reactor

The fast breeder reactor uses a uranium cycle to refuel itself. However, its excess bred fuel can best be exploited in a high-temperature gas-cooled reactor, a thorium-cycle-based converter type. For this purpose, fissile feed material such as U-233 can be bred in thorium blankets around FBR cores. Thus both reactor types can be used to complement each other, a fortunate circumstance in the effort to successfully meet the long-range energy crisis.

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Based on a paper contributed by the ASME Nuclear Engineering Division.

In considering the incentive for operating both fast breeders and HTGR's in a power program, see Fig 1, the first aspect requiring clarification concerns the extent to which an external supply of U-233 could benefit the thorium-uranium thermal reactor fuel cycle.

The precise extent of the benefit of being able to operate the HTGR system from the start on U-233 is a much more complex question than might be supposed, for the prime goal of minimal power cost inevitably involves compromise in design between conflicting issues. Thus, getting the most benefit from an improved starting fuel calls for complete design reoptimization. Indeed, this is one reason why having such fuel available from the start is much more advantageous than breeding it in during reactor life, for the latter approach largely precludes the design reoptimization necessary to extract full benefit. By looking at what we presently get with U-235 start-up and at some of the compromises involved in design for the alternative case, we may get some idea of the potential rewards of being able to design for the best fuel from the start.

The conversion ratio for present HTGR designs, when initially operating on U-235 without U-233 recycle, approaches a steady-state value of 0.60 after about 10 years of operation. Even when all the U-233 in the spent fuel is recycled and equilibrium is reached, a conversion ratio of only perhaps 0.7 is attained. This might seem surprising for an "advanced converter" which, in principle, could achieve near-unity conversion on the thorium U-233 cycle. It is, therefore, important to observe that these figures do not arise from inherent design limitations, but are simply the result of adjustment to achieve minimal power cost.

It turns out that, under prevailing conditions, it is more economical to take advantage of the HTGR core's special ability to achieve very high rating than to exploit its full potential as a near-breeder. Introduction of U-233 from the start changes this situation by providing increased conversion without corresponding loss of fuel rating. Indeed, the accompanying increase in effective fission cross-section and the improvement in age-peaking factors substantially raise the rating capability. Thus, while there will still be a new optimum conversion less than the ultimate, this value can be much higher than the present figure. This is illustrated by the fact that a simple change from U-235 to U-233 with appropriate fertile-to-fissile ratio adjustment alone would raise conversion by at least 0.1. The use of more frequent fueling or on-line refueling would allow another increment of about 0.05. The rapid rise of the "fuel amplification" term [1/(1-CR)], as unity conversion is approached, further acts to raise the optimum degree of breeding. It also makes the optimum much "flatter," allowing further breeding gain for little penalty.

Another feature of present limitations is the slow U-233 buildup associated with low-conversion operation. The available U-233 content of fuel recycled from HTGR's started on U-235 never, in fact, amounts to more than about one-third of the total fissile feed requirements of these reactors. Thus restricted, HTGR's do not fully exploit the U-233 advantage. Availability of U-233 from a high-gain breeder would, therefore, provide a route for eventually making use of the full, undiluted benefits of U-233.

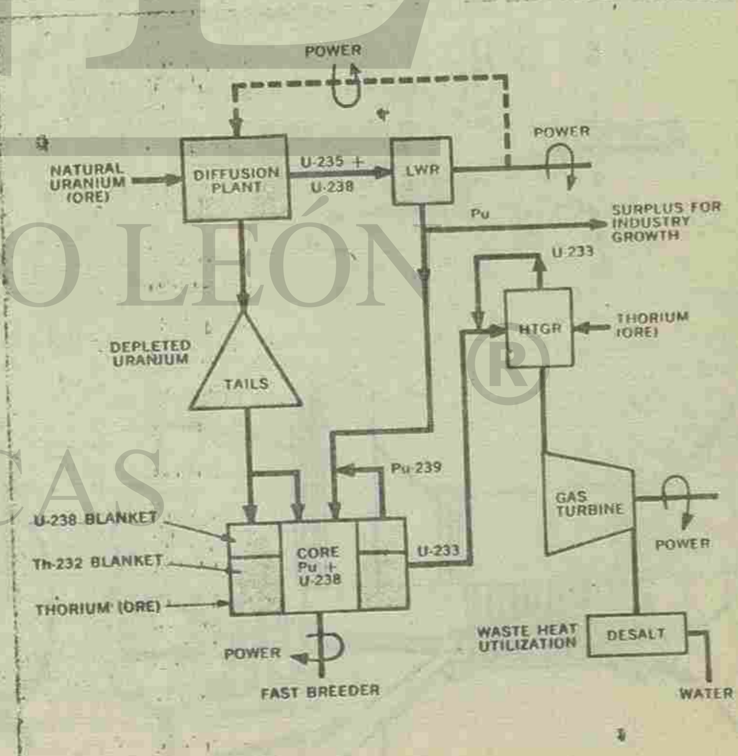
Optimal Association of FBR's and HTGR's

Systems analysis studies by the USAEC and national laboratories have had, as an objective, the determination of the probable energy growth patterns by power plant type, based on projected national energy requirements, resource availability assumptions, and power plant economic assumptions. The results of these studies have contributed, probably unwittingly, to the impression that one type of nuclear power plant will triumph over all other candidates. However, the ultimate emergence of the FBR as the predominant source of energy in these analyses should not be too surprising in view of the assumptions and the constraints applied. The most influential assumptions in the studies were probably: (*a*) the relative capital cost data for different reactor types, (*b*) the value of U_3O_8, and (*c*) the type of bred fuel allowed from the FBR plants and the disposition of this fuel. The last point is particularly important in the very long range. In all cases, it was assumed that excess plutonium was bred from natural or depleted uranium blankets. While plutonium is, of course, the most ideal fuel for fast-spectrum reactors, thermal-spectrum reactors would be expected to profit more from the production of U-233 in thorium blankets. The higher conversion ratio attainable with U-233 would also allow a larger number of thermal-spectrum reactors to be supported by a fixed source of bred fuel.

In the future energy era, when a bred fuel surplus can be expected, fuel supply costs will become a less important factor in the economic selection of reactor types. Capital costs of nuclear plants will then become even more dominant than is currently the case. Under these conditions, the thermal-spectrum HTGR, particularly with gas turbine and dry-cooling towers, should offer a considerable economic advantage over FBR plants. Even under these circumstances, however, the economic advantage of the HTGR can be enhanced if an ample source of U-233 feed fuel is provided by a relatively small number of FBR plants.

With the availability of FBR plants as fuel factories and HTGR plants as energy factories, the basic question becomes one of the optimum ratio of HTGR plants to FBR plants. The upper limit for this ratio depends on the FBR breeding ratio, the

Fig. 1 Integrated nuclear power generation.



HTGR conversion ratio, and the rate of growth of new energy requirements. For an FBR breeding ratio of 1.5 and an HTGR conversion ratio of 0.9, approximately four HTGR plants can be supported by one FBR plant, assuming energy generation has reached a steady-state condition, i.e., no growth. While the growth of electrical energy is currently at a rate of about 7 percent per year, one would expect that over the period of 100 years or more, some asymptotic energy generation level will be reached, after which the level of energy generation will stabilize. In 50 years from now, the rate of growth of electrical energy is expected to be between 3 and 4 percent per year. For a growth rate of 3 percent per year, the ratio of HTGR to FBR plants would be about two to one.

The optimum balance between HTGR and FBR plants has still further ramifications. If the capital cost advantage of the HTGR over the FBR is significantly large, as it indeed might be, then further advantages may be realized with the system by operating the HTGR off its economically optimum condition in order to increase the conversion ratio still further and allow an even larger number of the still more economic energy plants relative to the fuel-producing plants.

Another variant in operating strategy might involve the optimization of load assignments to the FBR and HTGR plants. Generally, the overall load factor for the entire energy system would probably be less than 70 percent. By operating the FBR plants at their maximum availability, say 80 percent, the production of fuel could be maximized, again allowing a larger fraction of the total number of power plants to be the lower-cost HTGR plants.

With an HTGR conversion ratio close to unity, relatively modest changes in operating strategies can lead to quite significant economic rewards.

The Role of the HTGR

Since fast breeders produce more fissile material than they consume, being, in this sense, "fuel factories," and at the same time operate at temperatures allowing efficient power generation, the need for any other kind of reactor at all might be questioned. If fuel cycle costs were the only factor to be considered, a power program dependent entirely on fast breeders would certainly appear attractive. However, far more must be considered in determining real total system economy, and it is this latter criterion, and not just fuel costs or even global fuel conservation issues, that really determines the acceptability of a particular reactor system.

Total nuclear power costs are dominated by capital charges, and, in the case of the efficient FBR/HTGR breeding system combinations we are discussing, this would be even more evident. A prospective fuel cycle cost of approximately 1 mill/

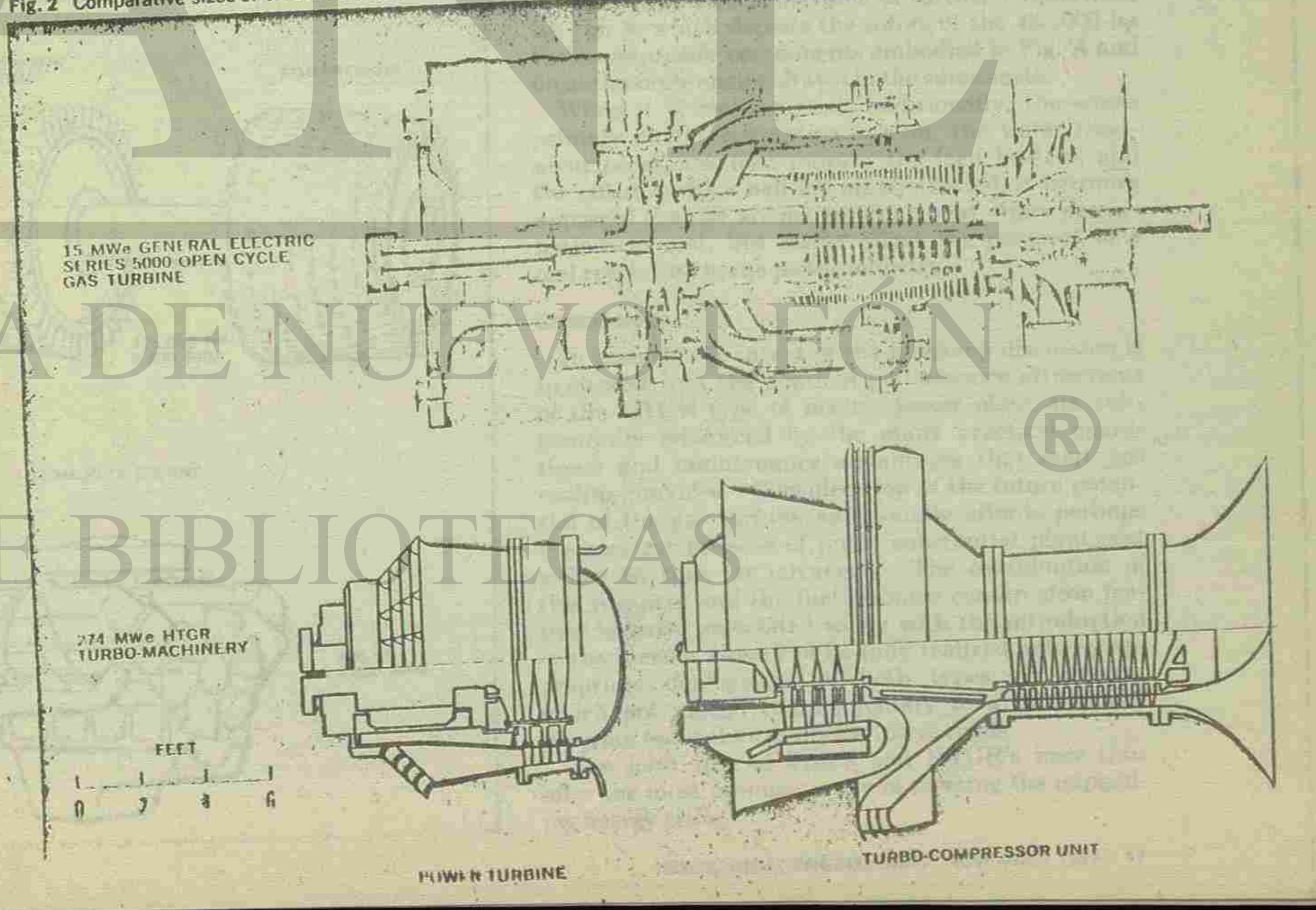


Fig. 2 Comparative sizes of turbomachinery.

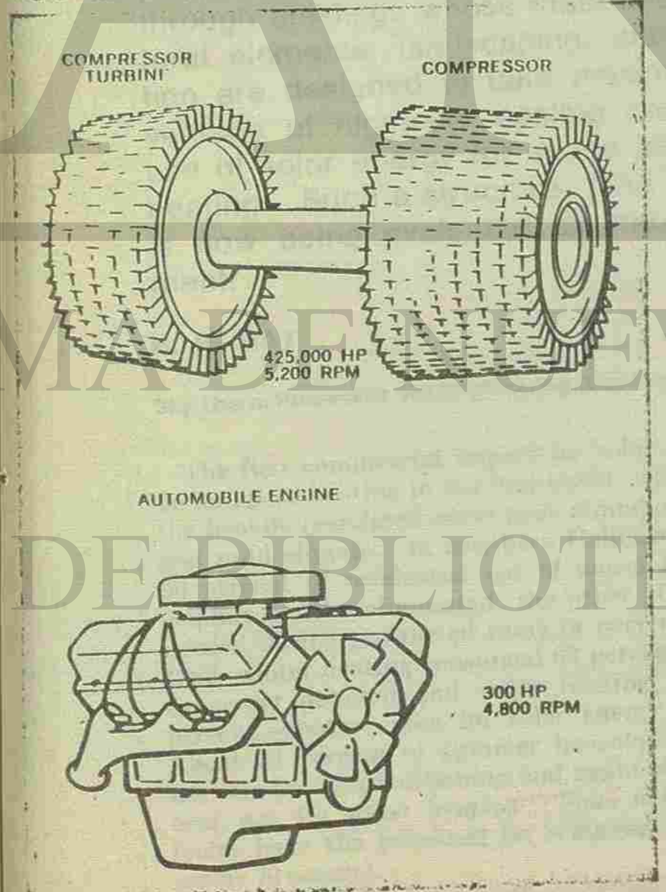
kwhr, for example, would amount to less than 12 percent of the generating costs associated with a plant having a capital cost of $400/kw. A modest capital cost increase can thus easily wipe out a large fuel cost advantage. Furthermore, even a small outage time has the same effect, for by far the greater part of operating cost is independent of whether or not such a plant is working.

What really sells a nuclear power plant, then (particularly one of the new generation), is the cost of building it and the likelihood that it can be kept going, as indicated by demonstrably simple maintenance, as well as confidence in reliability. These issues, together with factors affecting freedom of site choice, are what really count. It is in these areas that the prospects of the fast breeder are less clear, and indeed require extensive further study.

The issues raised are largely matters of practical engineering, rather than physics, and are concerned not only with the capital cost and other characteristics of presently constructed types of plant, but, more importantly, with the impact of future requirements and technical developments. Prominent among the latter are the increasing pressures of environmental factors and the possibilities offered by successful adaption of the closed-cycle gas turbine to the needs of nuclear power.

The connection between these last two factors is simply that, because of the inherently much higher mean temperature level of the gas turbine's heat reject, it can be much more readily adapted to the needs of dry cooling. In fact, about ten times less air (correspondingly heated to ten times the temperature rise permissible with a steam plant) suffices to dispose of the gas turbine's heat. Thus, the advent of the closed-cycle gas turbine, practically adaptable only to the HTGR's high gas temperature, is of particular importance to the solution of heat-rejection problems and thereby provides a much wider freedom of site choice.

Fig. 3 Turbocompressor rotors for 250-Mw nuclear gas turbine.



Even in the absence of a dry cooling requirement, the attractions of the direct-cycle nuclear gas turbine in terms of plant simplification and capital cost savings are impressive and add greatly to the prospect of the capital cost reduction so essential to achievement of really economic nuclear power.

A second, perhaps less dramatic, but certainly more appropriate, illustration of the compactness typical of closed-cycle machinery is provided by Fig. 2, which compares the size of such a system with that of a representative open-cycle system as presently used for power peaking duty. In this case, the striking point is the enormous increase in power for roughly similar size brought about mainly by the pressurization of the closed-cycle's exhaust.

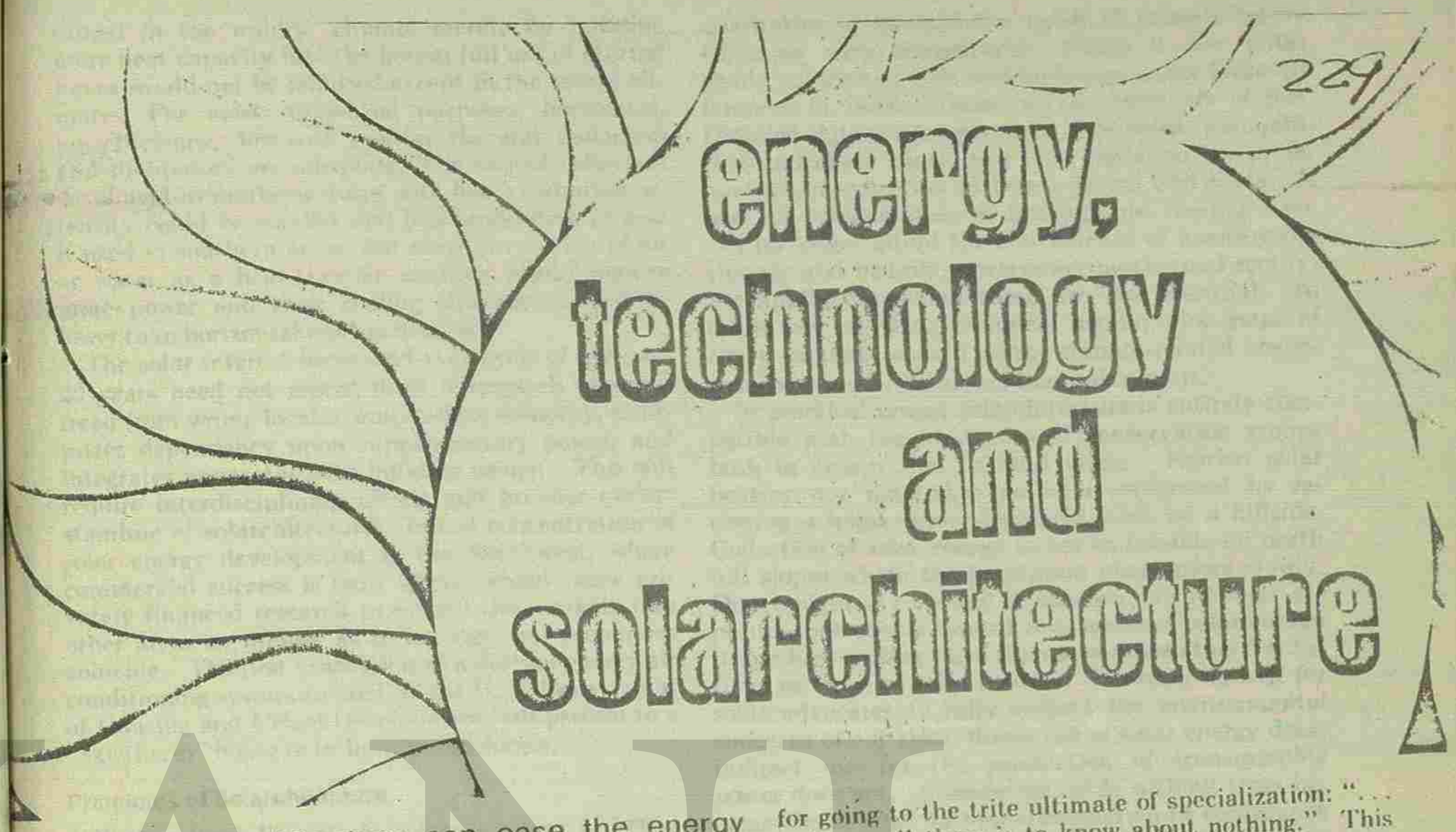
Fig. A conveys something of this potential by illustrating graphically the extreme compactness of the closed-cycle gas turbine, which allows its complete incorporation into spaces in the reactor vessel that were needed to house solely the boilers of a steam nuclear power system. The degree of the reduction in machinery size achievable is further emphasized by Fig. 3, which depicts the rotors of the 425,000-hp turbocompressor components embodied in Fig. A and an automobile engine drawn to the same scale.

When it is realized that, additionally, the whole primary circuit circulation system, the water treatment plant, the feed pumps, the feed heaters, and the entire turbine hall are all eliminated, it becomes apparent that we are not talking about minor perturbations to cost, but rather about the prospect of a real revolution in the power industry.

Conclusions

In essence, the intent of the foregoing discussion is to suggest that the nominal performance attractions of the HTGR type of reactor power plant are substantially reinforced by the many practical operational and maintenance advantages that inert gas cooling provides. Consideration of the future potential of the gas turbine additionally affords perhaps the greatest promise of really substantial plant cost reduction thus far advanced. The combination of this prospect and the fuel resource conservation feature hitherto associated solely with the introduction of the breeder alone can be fully realized only by appropriate deployment of both types of systems, which are indeed complementary to a total power program and not virtually exclusive rivals.

The joint role of FBR's and HTGR's may thus offer the most promising way of meeting the impending energy crisis.



energy, technology and solarchitecture

Solar architecture can ease the energy shortage over the next two decades. It can reduce by 70 per cent the residential power needs in most of the Southwest through buildings whose materials, structural elements, landscaping, and operation are designed to take maximum advantage of night-sky cooling and direct use of solar energy for space and water heating. Such a structure, "Sky Therm," is now being evaluated by the government.

H. R. HAY

Sky Therm Processes and Engineering, Los Angeles, Calif.

The first commercial impact for solar energy will be for space heating in the Southwest, where most of the heavily populated areas have abundant sunshine and mild climate. In Southern California, perhaps 90 percent of residential use of power for thermal comfort can be eliminated; the other 10 percent is needed during protracted rainy or overcast days. In 1968, winter heating consumed 63 percent of domestic power demand and water heating required 15 percent—another area for solar energy direct use. About 62 percent of summer household electricity use was for air conditioning and again about 15 percent was for water heating. Thus natural energy forces have the potential for reducing home power use by 70 percent.

The air-conditioning load coincides hourly and seasonally with the peak power demand on the distribution system. Thus, there is strong justification for going to the trite ultimate of specialization: "... to know all there is to know about nothing." This particular nothing is outer space. Man made better use of it thousands of years ago than we do after physically penetrating it. To save power, we must return to the direct use of the night sky as a heat sink. There are advantages in coordinating this effort with the direct use of solar energy.

Mutually Advantageous

Facing a power shortage and brownouts, the Los Angeles Water and Power Department has stopped promotion of "Gold Medallion" all-electric homes. To prevent the crippling of industry and consequent unemployment, end use priorities for power may soon deny occupants of "electric homes" the thermal comfort which produces about 15.5 percent of the system demand. Southern California may be forced to use high sulfur oil that will increase smog problems; the city is on record as regretting its part in the air pollution formed by thermal power plants hundreds of miles away in the deserts. It is, therefore, advantageous for both utilities and industry to promote diurnal energy heating and cooling.

In addition to assuring comfort in periods of power brownout, natural air conditioning may also relieve the new house owner of unnecessary expenses. In Los Angeles, heating and cooling a 2000- to 2400-sq -ft house, plus water heating, costs $18.50 in a $24.00 monthly electric bill. Disregarding any rate change, 70 percent reduction by use of diurnal energy flux would result in a $17-saving. Applied to reduce a $25,000, 30-year mortgage on a house, this saving would permit paying off the mortgage seven years earlier with over $10,000 less interest calculated at only 7.0 percent, (a $12,700 saving at 8.5 percent interest rate).

Wherever heating and cooling are used in the Southwest, natural energy flux utilization can reduce tained in the mildest climate merely by building more heat capacity into the house; full use of diurnal forces would not be required except in the severe climates. For most residential purposes, horizontal, low efficiency, low-cost rooftop thermal collectors and dissipators are adequate. The sloped collectors developed in northern states with lower radiation intensity could be smaller and less prohibitive in cost if used in southern areas, but their circulation of air or water as a heat-transfer medium would require more power and their cooling efficiency would be lower than horizontal rooftop devices.

The solar interest boom-and-bust cycle of the past 20 years need not repeat itself if research becomes freed from wrong locales, emphasizes economy, minimizes dependency upon supplementary power, and integrates apparatus with building design. This will require interdisciplinary efforts and broader understanding of solarchitecture. Initial concentration of solar energy development in the Southwest, where commercial success is more likely, would cause privately financed research to extend the markets into other areas as rapidly as technology and economics coincide. The first evaluation of a diurnal energy air conditioning system funded by the U. S. Department of Housing and Urban Development will pertain to a "sky therm" house to be built in California.

Principles of Solarchitecture

Within local limitation, solarchitecture is better practiced as an art in developing countries than it is in the advanced regions of the world. By reviewing the basic principles, modernizing the technology, and analyzing the impact which solarchitecture can make on the power and pollution crises, we may recognize not only great potentials but we may also find reasons for reconsidering substantial portions of our way of life.

Solarchitecture, in the recent past, has not been so closely related to space heating with solar energy as it has to reduction of heat load through site selection, orientation, overhangs and brise soleils, fenestration treatments, and landscaping. This emphasis was directed toward lowering the operating cost of powered air conditioning. With seasonal peak demand for power now resulting from air conditioners, a national effort is being made to increase the amount of insulation in the walls and attics of new houses. Since this is intended to reduce solar radiation effects, solarchitecture is as directly involved as if the insulation were used to retain heat derived from solar collectors.

The future use of photovoltaic cells (mounted on the walls and roofs of buildings) to supply the electricity for those purposes for which the more efficient direct-use solar energy appliances are not adaptable will become an important aspect of solarchitecture. It is a very broad, interdisciplinary subject and it is fundamental to the development of economic use of natural energy forces.

Geographic Climatology

Geographic climatology is a developing science basic to the use of diurnal energy flux. Climate data provided by weather stations do not approach the qualitative or quantitative needs of solarchitecture. Climates vary recognizably within a few miles; shade patterns of hills and buildings create large differences in micro-climate within hundreds of feet. Detailed data on temperature, dew point, precipitation and cloud cover, and solar radiation are prerequisites for selection of house design and materials and for consideration of heating and cooling. We can no longer afford the convenience of ignoring the climate and installing overpowering thermal rectifying appliances where these are not essential. In terms not requiring technical acuity, plot maps of zoned property should reveal climate-related energy requirements for obtaining thermal comfort.

In practical terms, solarchitecture is entirely compatible with the objectives of conservation groups both in energy and in land usage. Neither solar heating nor night-sky cooling is enhanced by recessing a house under large old trees on a hillside. Collection of solar energy is not so feasible on north hill slopes where the vegetation grows more slowly. Direct night-sky cooling is independent of solar exposure, but efforts toward conversion of solar energy to produce cooling have the same orientation limitations as those of solar heaters. It would be well for solar advocates to fully respect the environmental concerns of our time; direct use of solar energy does; indirect use for the production of transmissible power does not. Abandoned fields without trees become choice sites for new construction in accordance with solarchitectural principles. Such fields allow freedom of orientation and for tree planting which avoids undesirable shading effects.

Structural Features

The high heat capacity of earth, stone, and brick is now little used to modulate diurnal energy effects in industrial countries. Costs of manufacture, transport, and erection of these materials for walls having required thickness for adequate heat storage are excessive—as is also the cost for concrete. Earth materials acquire new status through solarchitecture. Sand-filled cavity walls can add heat capacity and obviate the need for hauling sand away from some construction sites. More significantly, the ground can be better used as a heat sink.

Plastic moisture barriers permit use of slab-on-ground construction and also of walls that are built partially below ground level—especially where the annual mean ground temperature is within the comfort zone. Use of perimeter insulation has demonstrated that a slab-on-ground floor may be the most thermally stable element of a room; wall-to-wall carpeting is then insulation wrongly placed.

Heat storage is being studied by other investigators not only to better utilize solar energy but also to shift a portion of peak power demand to hours of lower load. Conventional electric heating and cooling devices operated during off-peak hours have their excess thermal effects stored in high-heat-capacity materials which are a source of thermal comfort during peak hours when the devices are not expected to be operable. Chemical salts and rocks have been used as heat storage materials, but the high heat capacity of low-cost water is made increasingly appeal-ing by impermeable plastic films whose use for water beds has altered opinions about water storage. During the past several years, the writer has advocated and patented ceiling ponds and "water walls" for heat storage in connection with the use of diurnal energy forces; such water storage may now become a necessity for conventional heating and cooling devices.

Owing to water imperviousness, insulation of the rigid, cellular plastic type has new applications. Sandwich construction permits exterior uses, but replacement of high-heat-capacity construction by such panels has aggravated the problem of abrupt internal temperature changes resulting from thermostat operation, nonfunctioning thermal control appliances or from opened doors. Rigid panels of moveable insulation, acting as a thermal valve for diurnal energy flux control, are a new solarchitectural tool not only for horizontal ceiling ponds but also for vertical surfaces.

Past Faults Corrected

The ambivalence of glass is now recognized. The conclusion is that either more glass must be used to obtain a multi-pane insulating effect or less must be used to reduce wall area subject to excessive thermal transfer. Overabundance of glass in the solar house built near Phoenix, in 1958, contributed greatly to the failure of that demonstration and to the loss of interest in solarchitecture as it was then practiced. Ironically, the same excessive use of glass, general in air-conditioned buildings today, has contributed to renewed interest in solar energy. Movable insulation is a useful means, inadequately used, for selectively controlling thermal flow through windows.

Although marginal economics and failure to supply hot water of sufficiently constant temperature were additional reasons why solar water heaters lost their partial acceptance in the West and in Florida, their bad esthetic appearance was another reason. Solarchitecture provides ways for overcoming unsightliness. The heater, for example, can be an integral, inconspicuous replacement of roof elements with a reduction in overall cost. Plastics also play a major role in lowering heater costs—perhaps rejustifying solar water heaters in the Southwest.

Solar stills built as community water-supply systems have not demonstrated economic feasibility for use in the United States. Solarchitecture may provide better success through modular rooftop designs. Serving indistinguishably as a ceiling and flat roof, a design using plastics is estimated to cost less than that of normal ceiling and roof construction. First acceptance of rooftop solar stills on a large scale will be near seacoasts and at locations with brackish water. Subsequently, bottled water purchasers will become users of stills. The largest market may later be found in the reassurance to people that recycled effluent from sewerage treatment plants has been redistilled on their own roofs.

A cold water supply, perhaps ice water in large volume, is not regarded as a family need except by sauna enthusiasts and some desert dwellers. The potentials for rooftop production of cold water and ice have been discussed elsewhere [2].[1] Interchangeability with other rooftop natural energy appliances may justify promotion for a limited market, such as food conservation in hot-dry-region vacation cabins where refrigeration may not be desirable owing to lack of electricity, uneconomic frequency of use, or pilferage.

Model House

The air-conditioning system interchangeable with these other appliances has been previously described in detail [3]. In Figs. 1 to 4 are pictures of a model of the house type that will be evaluated in California. Fig. 1 shows panels of insulation stacked during a winter day over the annex comprising a carport, utility room, and patio. The 10-inch-deep ponds between beams over the two-bedroom living area are enclosed in transparent plastic bags atop a black pond liner which waterproofs the roof and is subtended by a loadbearing metal ceiling. Solar energy collection heats the water to 85 F—a temperature held purposely low by adjustment of water depth. This low temperature reduces upward reradiation loss, prevents excessive room heating by ceiling radiation, and assures longer service from the plastics used. Fig. 2 shows the insulation spread over the ceiling ponds at night to prevent heat loss to the winter sky.

Fig. 3 indicates the summer daytime position of the insulation over the ponds to prevent their being heated by the sun. This position exposes the area over the annex where water heaters and solar stills may be installed for summer use. Fig. 4 shows the panels moved to uncover the ceiling ponds for radiating to the night sky the infiltrated and internally generated heat, which they received from the rooms during the day. The insulation in this position covers the solar stills and water heaters in the annex area and conserves their heat throughout the night. It is preferable to use the overhanging bays (shown to the front and back of the house) as the primary location of shallow water heaters, stills, water coolers, or ice producers; the insulation should then be moved independently of the roof ponds.

The success of this air-conditioning system was proved with a test room in Phoenix, Arizona, where American standards of comfort were maintained with ambient temperatures ranging from subfreezing to 115 F. The previously reported results [3] justified a more detailed evaluation of the Sky Therm system on a full-scale and normally occupied house.

Evaluation of Natural Air Conditioning

Arrangements for evaluation of the ceiling-pond air-conditioning system were made with California Polytechnic State University, at San Luis Obispo, through the School of Architecture and Environmental Design along with participation of staff members from the Environmental and the Electrical Engineering Departments. Because the San Luis Obispo climate is not sufficiently severe, the house has been built at Atascadero where the climate is similar to that of nearby Paso Robles, which has recorded extremes of 10 and 117 F.

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[1] Numbers in brackets designate References at end of article.

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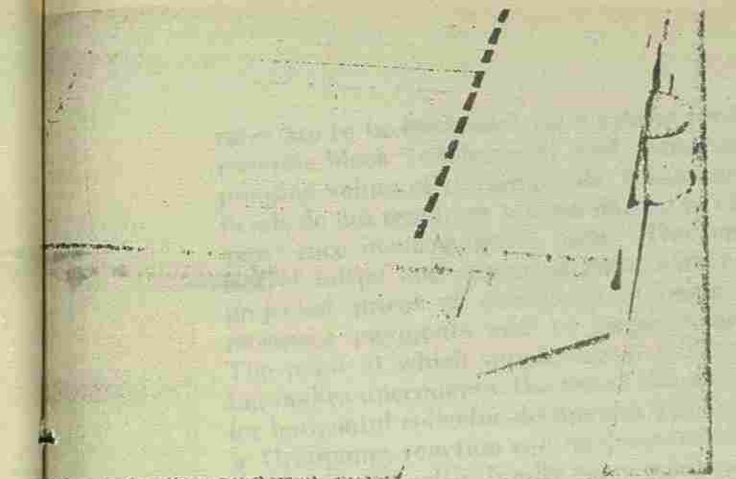


Fig. 1 Winter solar heating of ceiling ponds between beam; insulation panels are stacked over the carport, utility room, and patio.

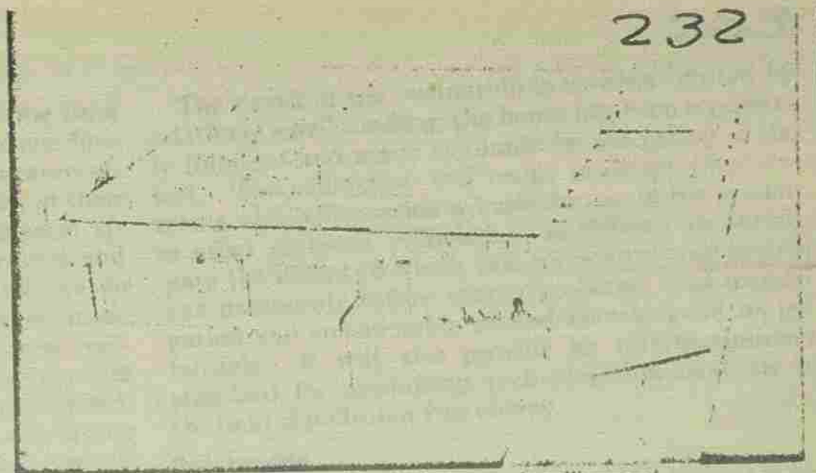


Fig. 2 Winter nighttime position of insulation prevents ceiling pond heat loss to the night sky.

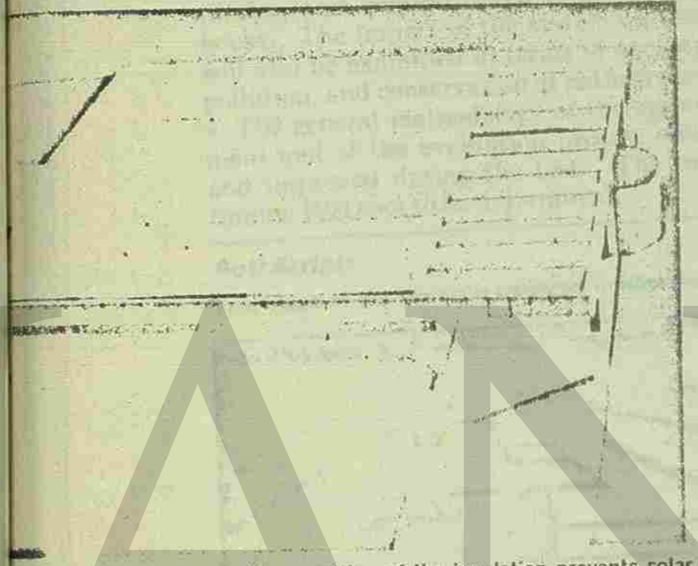


Fig. 3 Summer daytime position of the insulation prevents solar heating of ceiling ponds which absorb infiltrated and generated heat of living area.

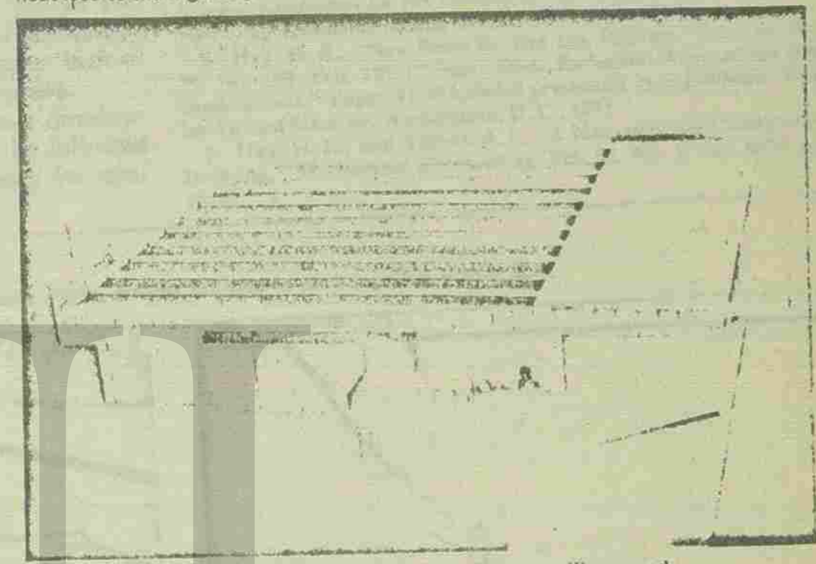


Fig. 4 Summer radiation to the night sky lowers ceiling pond temperatures below that of the underlying rooms and below that of overlying air.

The horizontal roof collector is not expected to meet the full heat demand because ambient air temperatures are lower, cloud cover is greater, and the location is 2 deg more northerly than the Phoenix location of the test room. More emphasis, therefore, will be given to heat collection on the south wall. Summer cooling, however, should be better than in the Phoenix test because nearby mountain ranges cause cooler nights which lower the mean daily temperature. Heat storage is expected to eliminate need for daytime cooling followed by nighttime heating—a local practice also used elsewhere in the Southwest.

The test house will not be open to public inspection during the year of normal occupancy and evaluation. Complete test results will be reported a year from now. Of the eight professors and the consultants collaborating in the HUD-sponsored evaluation each one has had private business experience and covers different specialties. The National Bureau of Standards has been invited to participate in the analysis of the data. Areas of evaluation are described below.

- The architectural advantages and limitations of the system will be considered as they are demonstrated by the test house and, additionally, through the plans of four other buildings including a low-cost design and a two-story structure.
- Construction aspects to be appraised are suitability in earthquake regions, costs, erection procedures, maintenance, as well as the required correlation between the architect, builder, and the system supplier.
- System design will be studied to determine any need to improve the framing and trackway for the movable insulation. A new beam design, specifically invented to minimize deflection of the trackway, will be tested. Factors being analyzed include wind load and lift; effects of rain, dust, and wind-blown debris; wear and alignment, etc. An estimate of service expectancy will be made.
- The effectiveness of the control mechanisms as well as their freedom from operational problems is to be investigated; both manual and automated movement of the insulation will be studied. Automation includes actuating devices responsive to time, temperature, and insolation.
- Thermal performance during occupancy by a family will be determined not only of room temperatures but also of zone control, the contribution of several heat storage innovations, and the isolation of heat inputs. Acoustical dampening of internal and external noises will be checked.
- Economic research will go beyond comparison with conventional heating and cooling. Insurance

rates are to be examined for a saving resulting from concrete-block construction and from unique fire-proofing values of ceiling ponds, which insurance officials do not regard as a flood hazard in view of their experience insuring water beds. The long-term effect of initial and operating costs with present and projected prices of electricity is being related to mortgage payments and to property depreciation. The point at which supplemental heating and cooling makes uneconomic the use of diurnal energy flux for horizontal collector-dissipators will be considered.

- Occupancy reaction will be determined concerning comfort and health, family economics, psychological and educational implications and limitations on ventilation and comfort when large groups are in the house. The impact of the system on the community will also be examined in terms of acceptance, lack of pollution, and conservation of natural resources.
- The general methodology of the system's development and of the evaluation process will be followed and improved during the test. The needs for continuing R&D are to be determined.

The depth of the evaluation is severely limited by relatively small funding; the house has been separately financed and made available for the period of the test. The evaluation will result in design improvements and will provide a basis for use of the system in other climates. Though it is difficult to anticipate the extent to which this solarchitectural system can ameliorate future energy problems, this investigation will considerably extend knowledge of its potentials. It will also provide an interdisciplinary standard for appraising technologic innovations in the field of pollution-free energy.

References

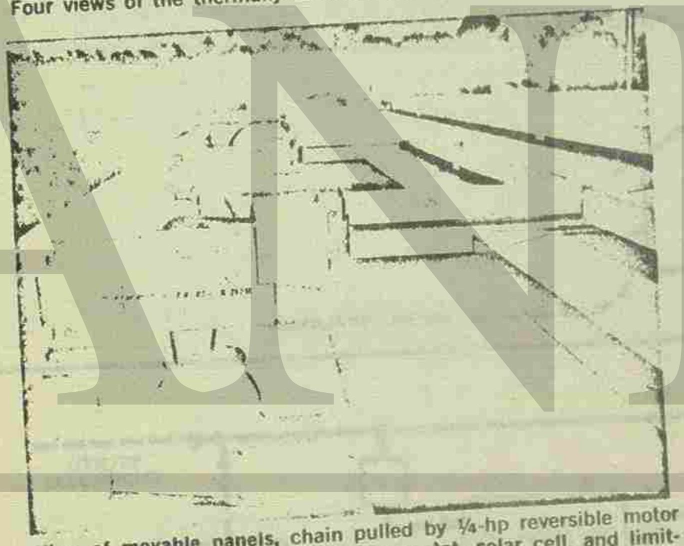
1 The Federal Power Commission, *The 1970 National Power Survey: Guidelines for the Growth of the Electric Power Industry, Part I*, Government Printing Office, Washington, D. C.

2 Hay, H. R., "New Roofs for Hot Dry Regions," *Ekistics*, Vol 31, No. 183, Feb. 1971; "Some Solar Radiation Adaptations and Implications," Paper 71-WA/Sol-3 presented at the ASME Winter Annual Meeting, Washington, D. C., 1971.

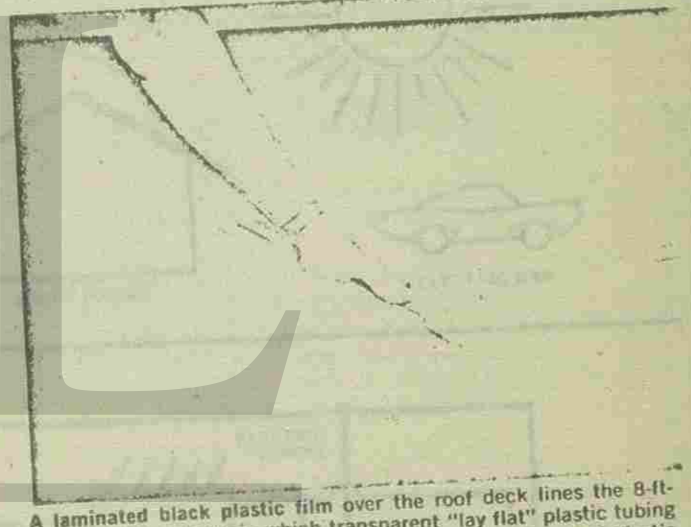
3 Hay, H. R., and Yellott, J. I., "A Naturally Air-Conditioned Building," *Mechanical Engineering*, Vol. 92, No. 1, Jan 1970, pp. 19–25.

Post Script:

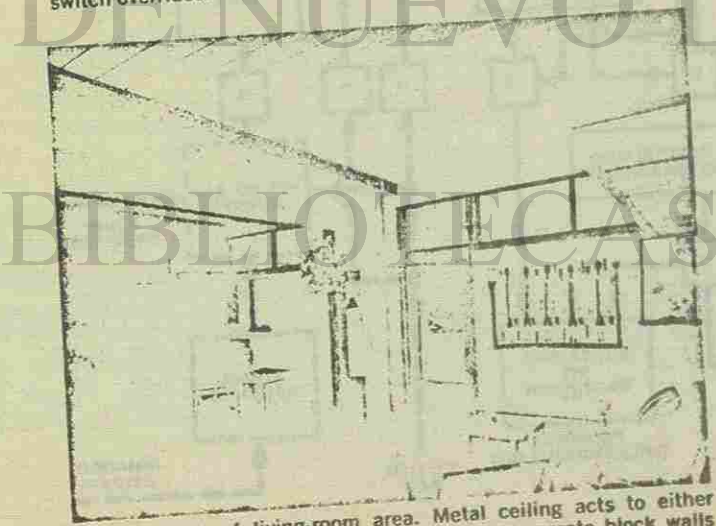
Four views of the thermally balanced finished house. Photo arrived too late to be integrated with article.



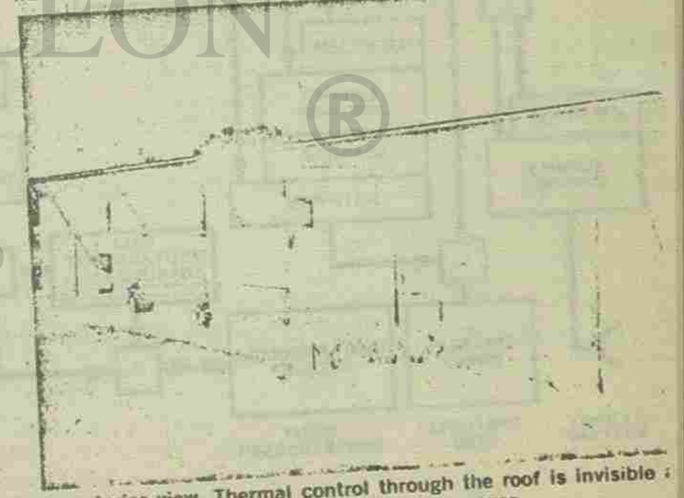
View of movable panels, chain pulled by ¼-hp reversible motor actuated by a time clock with thermostat, solar cell, and limit-switch overrides.



A laminated black plastic film over the roof deck lines the 8-ft-wide, 36-ft-long bays in which transparent "lay flat" plastic tubing filled with water forms the water beds. Tough resiliency of plastic water beds is shown by its reaction to "karate chop."



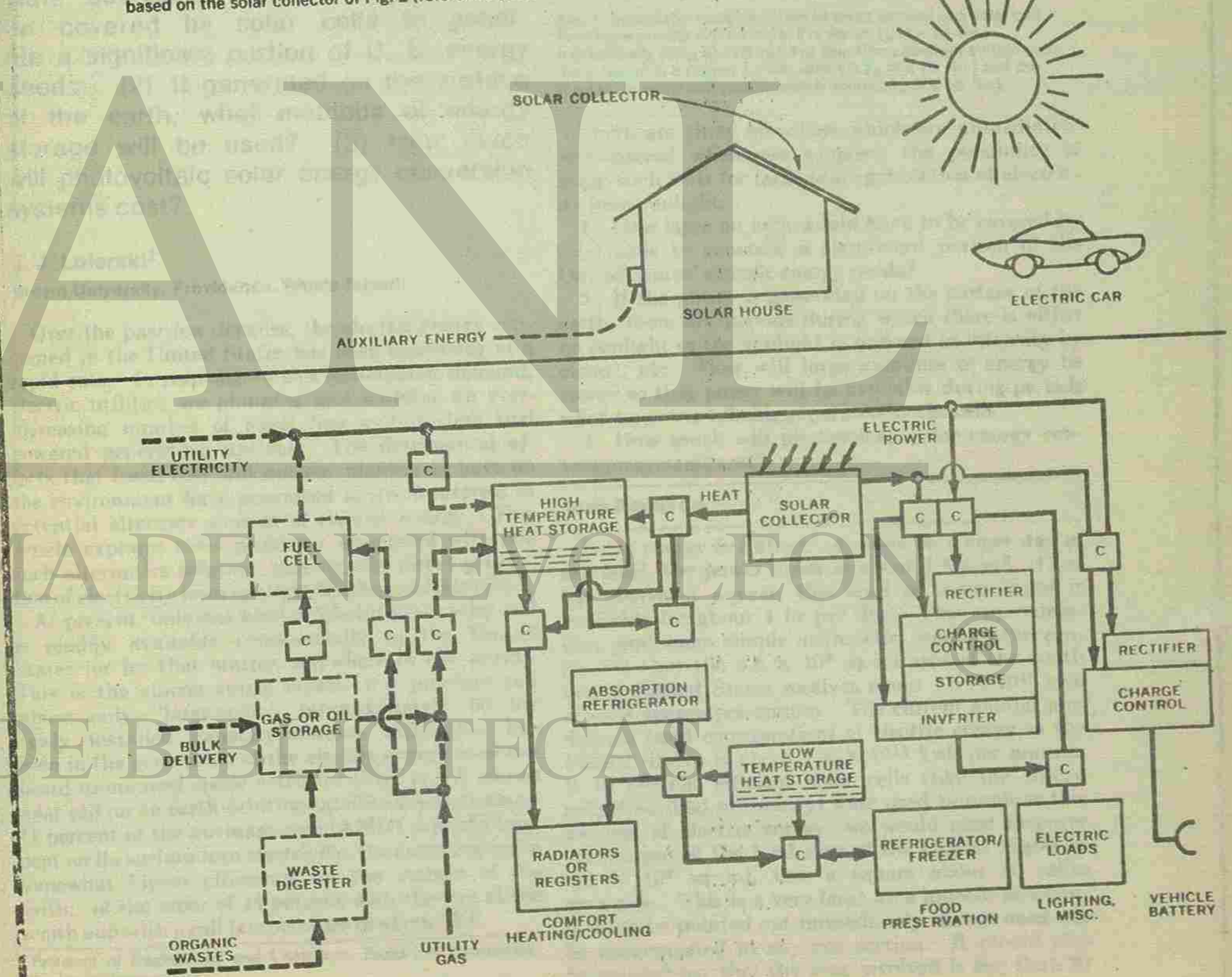
Interior scene of living-room area. Metal ceiling acts to either radiate or absorb heat and is supported by concrete block walls and lintels.



An exterior view. Thermal control through the roof is invisible ground level and occupies no interior floor space.

large-scale solar power photovoltaic

Fig. 3 Schematic of solar energy system for residential building based on the solar collector of Fig. 2 (reference [5]).



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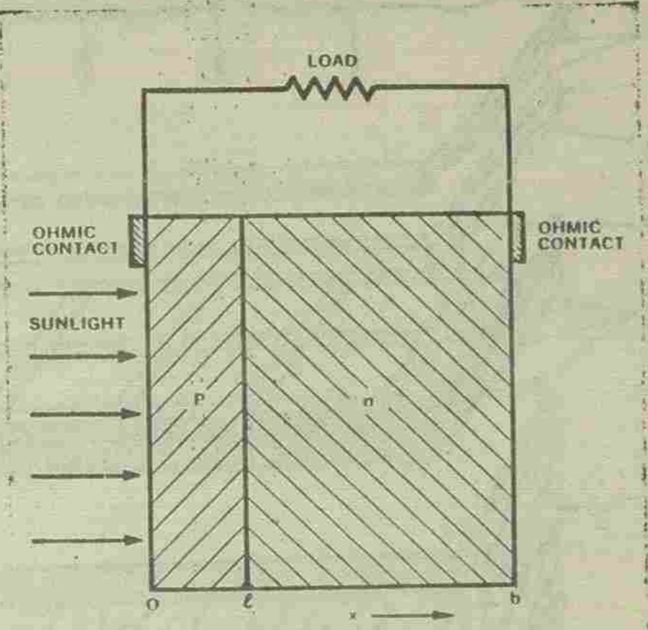

Fig. 1 Schematic representation of cross section of a solar cell. For single crystal silicon cells, ℓ is about 1μ (4×10^{-5} in.), b is typically 800μ (0.020 in.). For thin film cadmium sulfide cells, the p-region is a copper sulfide about 0.2μ (8×10^{-6} in.) and the n-region is cadmium sulfide with b about 20μ (8×10^{-4} in.).

Power via solar energy is moving inexorably toward center stage. Three immediate questions: (1) what area must be covered by solar cells to generate a significant portion of U. S. energy needs. (2) If generated on the surface of the earth, what methods of energy storage will be used? (3) How much will photovoltaic solar energy conversion systems cost?

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Over the past few decades, the electric energy consumed in the United States has been increasing at a rapid rate. In response to this anticipated demand, electric utilities are planning and building an ever-increasing number of fossil fuel and nuclear fuel powered generating stations. The detrimental effects that fossil fuel and nuclear plants can have on the environment have generated renewed interest in potential alternate sources of electric energy. This article explores some problems associated with one such alternative solution, namely, the direct generation of electricity from sunlight by photovoltaic cells.

At present, only one kind of photovoltaic solar cell is readily available commercially in the United States (or for that matter, anywhere in the world). This is the silicon single crystal p-n junction cell whose only "large-scale" (approximately 50 kw newly installed capacity/annum) utilization has been in the generation of the electric energy used on-board unmanned space satellites (Fig. 1). A silicon solar cell on an earth-orbiting satellite converts about 11 percent of the air-mass-zero (AMO) sunlight incident on its surface into electricity; the same cell has a somewhat higher efficiency on the surface of the earth: of the order of 14 percent with the sun at the zenith and with a cell temperature of about 75 F.

There are three questions which are immediately encountered when one proposes the possibility of using such cells for large-scale generation of electricity from sunlight:

1 How large an area would have to be covered by solar cells to generate a significant portion of the United States' electric energy needs?

2 If the power is generated on the surface of the earth, there are periods during which there is either no sunlight or the sunlight is reduced in intensity by clouds, etc. How will large amounts of energy be stored so that power will be available during periods when no power is being generated by the cells?

3 How much will photovoltaic solar energy conversion systems cost?

Area Required

Solar energy is diffuse: at noon on a clear day at sea level, the power input is about 1 kw/m^2. Over the course of a year, this level of power input is available for about 4 hr per day. This approximation, and some simple arithmetic, leads to the conclusion that the 3.6×10^6 sq mi area of the continental United States receives about 1.5×10^{16} kwh of solar energy per annum. The current annual production (and consumption) of electric energy in the United States is about 1.5×10^{12} kwh per annum. If 10 percent efficient solar cells (like the silicon cells described previously) were used to produce this amount of electric energy, we would need to cover 0.1 percent of the land area of the United States or 3.6×10^4 sq mi, i.e., a square about 60 miles on a side. This is a very large area indeed; however, it must be pointed out immediately that it need not be concentrated in any one section. It should also be pointed out that the area involved is less than 20 percent of the roof area of all man-made structures

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[1] Professor of Engineering and Chairman, Executive Committee, Division of Engineering.

Based on a paper contributed by the ASME Solar Energy Division.

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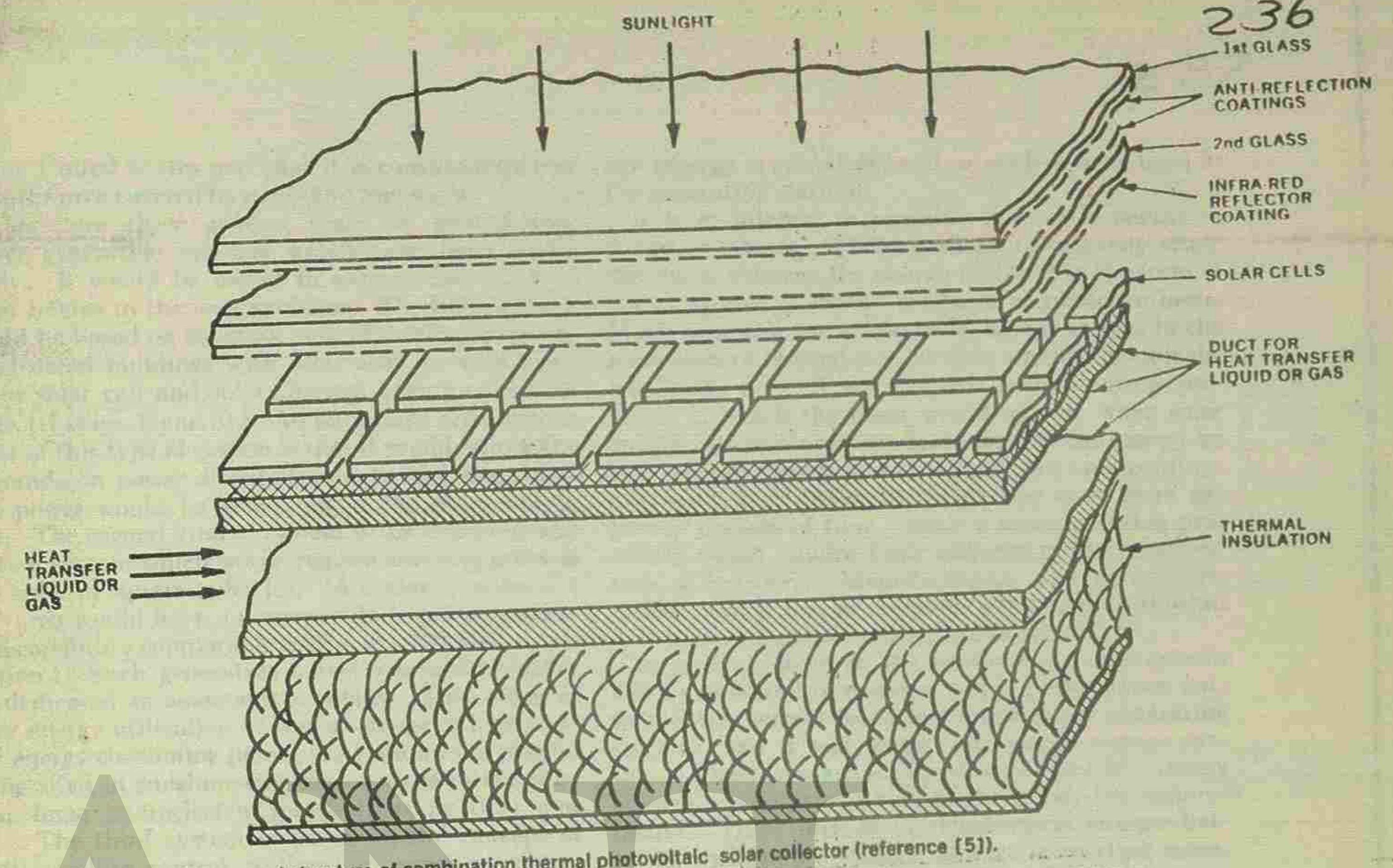

Fig. 2 Proposed structure of combination thermal photovoltaic solar collector (reference [5]).

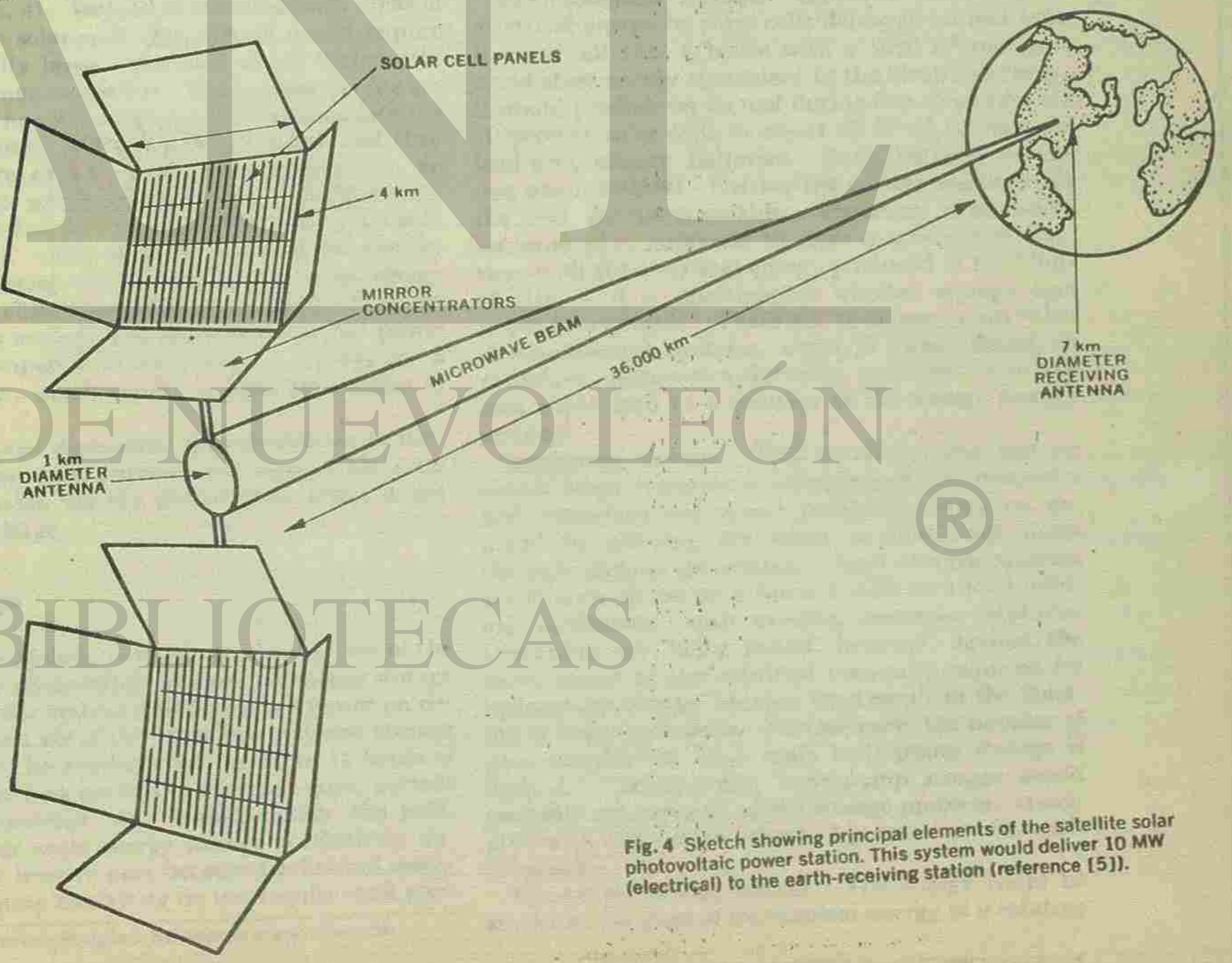

Fig. 4 Sketch showing principal elements of the satellite solar photovoltaic power station. This system would deliver 10 MW (electrical) to the earth-receiving station (reference [5]).

in the United States and that it is considerably less than the area covered by roads and highways.

There are three general kinds of photovoltaic power generation systems which have been under study. It would be useful to explore how each of them relates to the area problem. The first of these would be based on covering roofs of existing or newly constructed buildings with solar cells, or with combined solar cell and solar thermal energy collection units [1] (Figs. 2 and 3).[2] An important argument in favor of this type of system is that it would reduce the demands on power distribution networks since electric power would be generated at the consumption site. The second kind of system is the central power station system which would require covering areas of the order of square miles [2]. (A central station of 1 mi^2 area would have an average daily power generation capability comparable to that of a 100 Mw central station.) Such generating stations would probably be dedicated to some sort of plant. This mode of solar energy utilization evokes an image of high electric energy consuming plants (e.g., aluminum plants) being sited in sunshine-rich desert areas rather than near large hydroelectric installations as they now are. The third system is based on the concept of earth satellite central stations, transmitting power generated by solar cells to earth via microwave beams [3] (Fig. 4). Instead of covering large areas of the earth with solar cells, this system would require covering equally large areas with much higher efficiency microwave converters. The system has the advantage that the solar cells on a synchronous satellite would be exposed to the sun 24 hr a day and they could therefore deliver power on demand; i.e., no energy storage would be necessary. Furthermore, the total daily kwh/m^2 of microwave receivers would be about eight times what would be produced by solar cells covering the same area (the solar energy input to a satellite is a factor of 1.4 times the input at the earth's surface; the satellite generates power 24 hr/day compared to an average 4 hr/day for a surface system, which results in additional factor of 6).

From this brief discussion, it is reasonable to conclude that the area required for large scale solar energy conversion via the photovoltaic effect is not unacceptably large.

Energy Storage

As we have already pointed out, in the case of the satellite solar photovoltaic system, no energy storage is required: the system would produce power on demand. In the case of the other two systems, storage would have to be available for the 10 to 14 hours of night and day long periods of overcast skies, periods of rain and snowfall, etc. Unfortunately, the technology of large scale energy storage is relatively undeveloped, at least in part because traditional methods of generating electricity do not require such storage (energy is stored in fossil or nuclear fuels used in the generating station).

It is of interest to examine how solar energy is stored in nature. Photosynthesis occurs only while the sun is shining; the energy is stored in the form of chemical energy in the products of photosynthesis. Much of man's use of electrical energy results in the manufacture of products, be they metals, chemicals, machines, etc. If we devised manufacturing processes in which the plant would operate when solar energy was available, we could harvest the energy by collecting the product of the plant, not on a continuous basis, but rather by integrating over more extended periods of time. Such a manufacturing procedure would require basic changes in the organization of industry. Manufacturing, like agriculture, would operate not on demand, but rather in rhythm with a natural phenomenon; i.e., sunlight.

In general, however, the photovoltaic solar system will be expected to conform to the performance pattern of the current fossil fuel and nuclear generating stations, and it will require an energy storage system. There are a number of such possible energy storage mechanisms which might satisfy the requirements. These include electrochemical storage batteries, hydropump storage, storage in rotating masses, and storage in the form of hydrogen gas.

Electrochemical Storage. Consider generation of electrical energy by solar cells deployed on roof tops. It turns out that a house with a 2000 ft^2 roof area could store energy equivalent to the electrical energy it would produce on its roof during five clear days via 10 percent solar cells in about 50 ft^3 of commercial lead-acid storage batteries. Such batteries would cost about $600.00. Neither the volume required nor the cost are unreasonable. However, if lead-acid batteries were supposed to store a substantial fraction of all the electrical energy produced in the United States, it is questionable whether enough lead would be available. There are, of course, many other electrochemical systems, some of them based on abundant, inexpensive elements, and research in this area could lead to a solution of the energy storage problem.

Hydropump Storage. This involves using electric energy when available to pump water into reservoirs and extracting the stored potential energy on demand by allowing the water to flow back down through turbine generators. Such storage systems are already in use on a limited scale as a load leveling mechanism with existing generator stations. Objections are being raised, however, against the construction of the artificial reservoirs required for hydropump storage because they result in the flooding of large land areas. Furthermore, the number of sites suitable for large scale hydropump storage is limited. Consequently, hydropump storage would probably not solve all of the storage problems associated with large scale solar cell generation of electrical power.

Storage in Rotating Masses. The energy could be stored in the form of mechanical energy of a rotating

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[2] Numbers in brackets designate References at end of article.

mass. In this case, a motor-generator is operated as a motor when excess electrical power is available and it sets a "flywheel" in rotation, ultimately at very high speeds. Energy is extracted by allowing the rotating mass to drive the motor-generator as a generator. The system is, therefore, analagous to hydropump storage.

High density energy storage would require specially shaped flywheels composed of very high strength material capable of tolerating the high stresses which would develop at the extremely high speeds encountered in operation. No large scale use has ever been made of such flywheel energy storage; considerable research and development would be needed before wide scale application could become possible.

Storage in the Form of Hydrogen Gas. Recent studies of the possibility of energy storage in the form of hydrogen gas suggest that this could provide a solution to the problem. The hydrogen would be produced by electrolysis of water, an inherently very efficient process. The hydrogen could then be distributed from the central station via pipelines or perhaps in the form of liquid hydrogen. The energy could be recovered from the hydrogen through fuel cells which are very efficient converters. There are, of course, safety problems associated with the use of hydrogen and perhaps using the hydrogen to produce more easily handled compounds might be a preferred solution to the problem. Hydrogen as the energy storage medium is relatively unexplored, and again research and development must be expended to determine its full potential.

In summary, there are a number of large-scale energy storage methods which could potentially satisfy the requirements arising from large-scale solar cell electric power generation systems.

Costs of Conversion Systems

The most serious impediment to large scale photovoltaic solar energy conversion lies in the cost of currently available reliable, long-life, acceptable efficiency (>5 percent) solar cells. Although the photovoltaic effect is very commonly encountered in semiconductors, there are only two different semiconductor solar cell systems which are at a level of development sufficient to allow a credible analysis of their potential cost to be conducted. One of these is based on the single crystal silicon solar cell referred to initially; the other is based on the thin film cadmium sulfide cell. Each falls short of meeting the requirements for large scale solar energy conversion systems, though for different reasons.

The silicon cell is reliable, long-lived, and has a respectable solar energy conversion efficiency in excess of 10 percent. The only significant application for silicon solar cells has been supplying on-board electric power for unmanned space satellites. This involves a very small total power generating capacity, of the order of 50 kw peak power generation capability added per annum. The current cost of silicon cell arrays determined by this market is about $7000/m². In a recent analysis of the allowable costs of solar arrays intended for various applications, Wolf [1] concluded that the maximum allowable cost of solar arrays intended for central station power supplies is about $2.30/m²; for solar cell systems deployed on roof tops of buildings, $3.00/m²; and for solar cells to be deployed in a space central station system, $45.00/m². A reduction in cost should occur if the market were to expand from the current level of peak power production capability of 50 kw/annum to levels in the vicinity of tens of millions of kw/annum required to make a significant impact on the national energy budget. However, while a cost reduction by a factor of 100 seems attainable by making currently conceivable changes in production process, it is not evident that silicon systems based on current concepts can ever reach cost levels in the $2.00 to $3.00/m² level [2]. Examination of the added cost contributed at each stage in the manufacturing process indicates that the principal cause of the high cost is the need to make single crystals.

It is for this reason that the thin film CdS cell is attractive. The active part of this solar cell is a thin (10μ) polycrystalline film of CdS onto which an even thinner (0.1μ) layer of a copper sulfur compound film is grown. Recently, the Dupont Co. estimated that large areas of this kind of cell could be made for costs in the vicinity of $5.00/m² [4]. However, the current level of understanding of the photovoltaic effect in this system is not good enough to lead to the controllable fabrication of reliable, long-lived cells from CdS. Furthermore, their efficiency is in the vicinity of 5 percent, and it is not clear that it can be increased to levels comparable to those achieved in silicon.

Thus, with respect to cost of solar arrays, further research and development are required before it can be ascertained whether the cost levels required for large scale photovoltaic solar energy conversion are economically feasible.

Summary

In this article we have examined three objections commonly raised against the feasibility of large-scale generation of electric power by converting sunlight into electricity with the help of solar cells. It was concluded that the area needed for such power generation is not unreasonable; that methods of energy storage are available, and that there is reason for optimism with respect to reducing the cost for large-scale power generation from sunlight.

References

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