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SCIENCE AND THE CHALLENGES AHEAD

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[1] Term expired May 10, 1974.

[2] Reappointed in 1974.

SCIENCE AND THE CHALLENGES AHEAD

REPORT OF THE NATIONAL SCIENCE BOARD

NATIONAL SCIENCE BOARD
NATIONAL SCIENCE FOUNDATION
1974

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LETTER OF TRANSMITTAL

December 1, 1974

My Dear Mr. President:

I have the honor of transmitting to you, and through you to the Congress, the Sixth Annual Report of the National Science Board. The report is submitted in accordance with Section 4(g) of the National Science Foundation Act as amended by Public Law 90-407.

In this report, *Science and the Challenges Ahead,* the Board examines some of the major problems facing the Nation and the world: population growth, health care, food supply, energy demand, mineral resources, climate changes, and environmental alteration. The report identifies aspects of these problems which could be alleviated by science and technology and assesses the adequacy of present scientific knowledge for providing such help.

The primary contributions which science and technology can make in meeting these challenges are better understanding of the problems and the development of alternate strategies and technologies for attacking them. Present knowledge is inadequate for these purposes. Major advances in virtually all the sciences are required to expand and deepen the understanding of these problems and their interconnections before strategies and technologies of assured effectiveness can be developed.

Toward these ends, the Board recommends that the Nation's research efforts be expanded substantially in the years ahead. A part of the increased efforts should be directed to basic and applied research on problems now confronting the Nation, such as those discussed in this report. Another part needs to be reserved for "untargeted" basic research which is not tied specifically to present problems, but is aimed instead at advancing general scientific knowledge. This research may contribute to alleviating present problems, but its principal benefit lies in providing knowledge needed for meeting problems of the future.

In calling for greater research expenditures—by both the Federal Government and the private sector—the Board is mindful of the present state of the economy and of measures taken and contemplated for strengthening it. Many of the problems discussed in this report, in fact, have impaired the economy and are likely to continue to aggravate it until the problems are alleviated or solved.

The difficult decisions that must be made in these circumstances involve perplexing choices concerning priorities and the allocation of our limited national resources. What should the Nation's priorities be, and how should our resources be divided among them? What proportion of the Nation's resources should be devoted to research? And of these resources, what is the proper mix of attention to problems of today versus those of tomorrow, and to the immediate causes of our problems versus the more fundamental ones?

These decisions will influence and shape the future of our Nation. They can be made only by the President and the Congress.

This report was prepared by the National Science Board in the hope that it would serve as a resource to the Executive Branch and the Congress for enhancing the contribution of science and technology in improving the quality of life in this country and in the world.

Respectfully yours,

H. E. Carter

H. E. Carter

The Honorable
The President of the United States

ACKNOWLEDGMENTS

The preparation of the report, *Science and the Challenges Ahead,* spanned a period in which the membership of the National Science Board changed. Those Members whose terms expired in May 1974 are: Dr. R. H. Bing, Dr. Harvey Brooks, Dr. William A. Fowler, Dr. Philip Handler, Dr. James G. March, and Dr. Frederick E. Smith.

Although these Members participated in the formulation of initial drafts, the final report is the responsibility of the continuing Members. Dr. H. E. Carter was Chairman of the Board during much of the period in which the report was prepared and is submitting it on behalf of the present Chairman, Dr. Norman Hackerman.

Many Members of the Board contributed individual sections of this report, and the entire Board spent considerable time in its planning and review. Dr. Robert E. Bickner (Public Policy Research Organization, University of California at Irvine) assisted the Board in the early development of the report. The Board is deeply appreciative of the assistance of Dr. Robert W. Brainard of the National Science Foundation, who served as Staff Director throughout the later stages of the preparation of the report.

The help and cooperation of many other persons in the National Science Foundation are also gratefully acknowledged. The National Science Board Office provided outstanding administrative and secretarial assistance throughout the entire period of the preparation of the report.

CONTENTS

INTRODUCTION

Man's success in meeting challenges of the past is due largely to his insight and the ability to share it with present and future generations. Will man's knowledge of himself and of the physical and social environment be adequate to the tests that lie ahead?

Some of the challenges are as old as the human species itself. One of these is the challenge of the unknown, which is reflected in man's unremitting curiosity about himself and the world. Another is represented by threats from nature, in the form of disease, famine, and the elements. And a third class consists of social problems, ranging from international conflict to societal strife and interpersonal discord. These three classes of challenges, which overlap and influence each other, have changed in detail over time but still remain.

A fourth type of challenge has emerged recently and is growing rapidly. This is the challenge posed by man's increasing power to create his future. He has acquired the knowledge and means to alter the course of natural events and to shape the conditions of human life. Man's own actions, more than nature, now determine the size of the human population, its distribution around the globe, and the state of its health. His patterns of consumption produce a growing demand for food and fiber, for energy and materials—a demand that can neither be reduced nor met without altering the economic, social, and technological character of life in the future. Man is developing the capability to control weather and modify climate intentionally, while his agricultural and industrial activities produce inadvertent changes. To a growing extent and in a variety of ways, man has the power to cause basic transformations of the atmosphere, the oceans, and the biosphere—some of which may be irreversible alterations that endanger the habitability of the planet.

Thus, man increasingly invents his own destiny—intentionally or unwittingly. The constructive use of such power requires all our will and wisdom.

The last category of challenges is the focus of this report. Principal attention is directed here because of the growing practical significance of this challenge and the corresponding need for urgent and sustained attention. Several facets of this broad challenge now loom as major problems: population, world food supply, energy, materials, climate, and the environment. The nearly simultaneous emergence of these problems suggests the close connections that exist among them. The fact that the problems are global in scope indicates their pervasive and fundamental character as well as the difficulty in confronting them effectively. In whatever form the challenge is met—actively or passively, internationally or nationally, knowledgeably or ignorantly, successfully or unsuccessfully—the choices made will shape much of man's future.

Although emphasis is placed on the challenge of man's increasing power, no implication is intended that the other challenges can be ignored; they are, indeed, so intertwined with the more recent ones that all must be met.

The first chapter of the report reviews briefly the more familiar challenges and discusses general aspects of the newer ones.

The second chapter examines several problems encompassed in the broader challenge of man's increasing power. The nature and scope of each problem is discussed, and the past and potential role of science and technology in alleviating the problem is noted.

The third chapter explores the adequacy of science and technology for helping to respond to such problems. For this purpose two recently initiated U.S. programs—one in the area of cancer and the other in energy—are taken as illustrative tests of the present capabilities of science and technology.

The fourth chapter presents conclusions drawn from these assessments and relates them to recent trends in the level and direction of the Nation's research effort.

The final chapter recommends actions and policies aimed at strengthening the scientific and technological response to present and future challenges.

I

CHALLENGES AND THE RESPONSE OF SCIENCE

This chapter discusses briefly the nature of the general challenges cited earlier—challenges of the unknown, of nature, of society, and of man's growing power to shape the future—and reviews the past and possible future role of science in helping to respond to them.

Challenge of the Unknown

The urge to know the unknown, to explore the unexplored, and to explain the unexplained is among the most universal of traits. Indeed, curiosity and exploratory behavior are exhibited not only by *Homo sapiens* but by other species of animals as well. Their prevalence suggests that such behavior constitutes a "biological imperative," crucial to survival.

All cultures, past and present, attempt to explain the origin, relationship, and fate of man and nature. Each culture fashions its own response, and the results have been as diverse as the cultures themselves, ranging from astrology to zoroastrianism. The response, in whatever form it may occur, shapes the aspirations, values, and intellectual life of the culture.

Science has become a predominant response of modern cultures, a response which differs from earlier ones in many ways. Science in some respects is limited in its goals; it does not, for example, seek answers to questions such as ultimate purpose. It concentrates instead on observing and measuring the tangible, often through the use of instruments which extend the senses into domains that are otherwise inaccessible. Science is cumulative in an evolutionary way; it builds upon its past but modifies itself by incorporating new insights superior in explanatory power to existing ones. It is also self-testing and self-correcting; errors may occur, but they are found and rectified eventually. These basic and unique characteristics of science make it the most successful response so far fashioned by man for pursuing and unraveling the unknown.

Curiosity is not the sole motivation for scientific research. The practical need for and the utility of scientific knowledge are often prime reasons for seeking such understanding. This is illustrated by astronomy, one of the oldest of the sciences, which was studied in earlier days for the purpose of improving navigation as well as for insights into the composition and organization of the universe. This dual motivation of curiosity and utility is found in all scientific fields. Thus, in addition to satisfying man's curiosity, science has proven to have great impact on everyday life—from changing the physical conditions of existence to the length of life itself. This potential utilitarian "bonus," which can be gained when scientific knowledge is applied to practical ends, is so sizeable in general that a motive for basic research is often the potential applications that may flow from it. This flow, however, extends in the other direction as well—applications raise questions requiring further research. In fact, the reciprocal relationship between knowledge and utility, between insight and application, focuses and invigorates each.

In spite of the advances made in scientific knowledge—and in part because of the unanswered questions such advances reveal—science still faces many challenges. Some of the more specific of these are noted elsewhere in the report. But perhaps the most general and fundamental challenge now facing science is that of achieving better understanding of highly complex phenomena that involve a large number of interacting components, i.e., systems of "organized complexity." The behavior of the global atmosphere, the organization and functioning of the human brain, and the dynamics of a social institution or a larger social system are examples of such phenomena which are little understood at present. (New insights from further research, however, may reveal that such phenomena are less complex than they now appear.)

Historically, science has advanced primarily through the study of less complex aspects of nature, by isolating individual components and seeking to understand their characteristics through observation, analysis, and experiment. The understanding of such relatively simple phenomena provides the basis for almost all modern technology. Problems of organized complexity, on the other hand, require a broad, integrative approach, combining the methods and insights from many individual scientific disciplines and, perhaps, even radically new concepts and methodologies that transcend individual disciplines. Large-scale modeling and simulation are needed to synthesize the diverse knowledge regarding these complex areas, to uncover the underlying dynamics of the problems, and to project the future course of their development. An indispensable tool in these efforts is the enormous data-handling capacity of computers.

Until the level of understanding of such complicated phenomena is significantly improved, science will fall short of meeting the challenges in this area.

Challenges from Nature

Recent history records a succession of advances against threats from the natural environment—disease, famine, the elements—yet many threats remain. Major battles against disease have been won since the turn of the century. Many infectious diseases have yielded to immunizations, to antibiotics, and to public sanitation. Typhoid fever, diphtheria, tuberculosis, and scarlet fever are largely controlled, while other diseases such as osteomyelitis and mastoiditis seldom occur in this country today. As recently as 1950 more than 20,000 cases of poliomyelitis were reported annually in the United States, but 15 years later the incidence had fallen to nearly zero.

There remain, however, numerous diseases and disabilities which take their toll. Among these are major killers such as cancer and heart diseases; serious disabilities such as arthritis, asthma, and diabetes; and many less prevalent or less serious mental and physical afflictions. Present scientific knowledge provides, at best, means for "managing" these afflictions and diseases, rather than for preventing or curing them. The inherently high cost of such management—the expense for the patient and the heavy claims on the often restricted resources of the health system—prevents even this limited health care from being available to all who need it. A prerequisite for prevention and cure is better understanding of the fundamental biological processes involved. Such knowledge is the basis—the only basis—for advancing beyond mere management to prevention and cure.

The reduction of "premature" deaths from disease has been largely responsible for the lengthened life expectancy in the United States—up from just under 50 years at the beginning of this century to almost 70 years by midcentury. The life expectancy of persons over 50, however, increased only marginally during the period with the greatest gains occurring for women. This illustrates why challenges remain in spite of past progress: as infant and adolescent mortality was reduced, adult diseases took a greater proportionate toll.

Significant advances have been made against famine and malnutrition, based in large part on increasing knowledge of agricultural and animal science, plant genetics, fertilizer, insect control, and food processing. But total success has not been achieved in spite of sustained advances in agricultural production. These gains have been offset by the rapid growth in human population (an increase abetted by the success in suppressing human diseases), by adverse climate and weather conditions in certain parts of the world such as the sub-Sahara region, and by several factors which inhibit equitable distribution and optimal consumption of foods. Furthermore, advances in food production have been achieved at considerable cost: the extensive use of fertilizers and pesticides has damaged the environment, and vulnerable monocultures have been substituted for the natural diversity of plant life. This illustrates how progress in dealing with one problem can generate side effects which may themselves become problems to be understood and alleviated.

Malnutrition is still very much a part of the world scene, in this country and elsewhere. And because its existence in many cases is due to cultural and social factors rather than to food shortages, *per se,* malnutrition represents a problem for the social sciences as much as for the biological and physical sciences.

Considerable progress has been made in providing protection from the normal threats of the elements. But the effects of hurricanes and tornadoes, major floods, long-term droughts, and earthquakes are still largely uncontrolled. In the past few years remarkable progress has been achieved in predicting the location and occurrence of earthquakes, leading to the possible development in the near future of an earthquake warning system. In addition to prediction, much now can be done to reduce the economic and human loss of earthquakes; advances in antiseismic design of housing, as well as improvement of regional zoning practices based on developing knowledge of the earthquake process, are now feasible. Even the eventual control of earthquakes is not beyond possibility, as suggested by recent experiments in which earthquakes were initiated and stopped by first injecting and then withdrawing water from deep wells.

The vulnerability to severe storms has increased, as a result of the greater density of population and valuable capital facilities. The early warning of such storms by weather satellites and other observational techniques, however, has greatly reduced the loss of life and damage to property that would have occurred. The ability to manipulate weather conditions purposefully and safely is perhaps just beyond present capabilities, whereas the ability to affect weather and climatic conditions, unintentionally and even unknowingly, grows daily.

This cursory review of some of the challenges from the natural environment does not do justice either to past successes or to remaining problems. It does, however, illustrate some general points. Challenges are endless; success with one problem often leads to the discovery or creation of others. Challenges are interrelated; progress in dealing with one problem may be enhanced or nullified by progress or failure in other related problems. And challenges are dynamic; apparent success in an earlier time period may become apparent failure in a later one. This does not mean that progress is an illusion. It means that new challenges emanate from change and from progress itself—from changes in the natural environment, from advances in knowledge, from changes in social values, and from expanded human aspirations.

Challenges of Society

The challenges in this category are almost limitless: international strife, discrimination, crime and delinquency, and the spectrum of interpersonal and intergroup conflicts. Individual and social problems appear to be intrinsic to social life itself. While the nature and extent of such problems change over time, and differ from one society to another; the benefits of social life are always accompanied by stresses that engender problems.

Virtually all present societies exhibit conflict and turmoil. There are several possible reasons for this in the case of the United States. American society is heterogeneous in race, in national origin, and in socioeconomic level. It is a rapidly changing society—culturally, physically, and technologically. It is sufficiently affluent to explore and innovate deliberately, trying and testing new ideas in all realms from business to religion, but its material affluence has not brought an equal measure of psychological well-being. It allows for a diversity of subcultures and variegated life styles. And it encourages the aspiration—but does not always provide the commensurate opportunity—for the social mobility and progress of each individual.

These are not the ingredients for a static and self-satisfied society. They produce instead an experimenting society that is dynamic and seeking and, therefore, sometimes frustrated. Strains on social institutions and individuals are likely to persist, and possibly even worsen, as the result of several disparate conditions and trends such as: declining birth rate and consequent aging of the population; high rates of inflation; limited access to medical care; a high level of crime against people and property; and differences between the races and sexes in employment opportunities and income.

Specific social problems may persist for long periods in spite of efforts to resolve them. A study of social trends by a presidential commission expressed concern about the level of crime; the extent of poverty; the "sprawl of great cities"; the role of women outside the home; and the "consumer and his perplexities." This study was published in 1933. Its contemporary tenor illustrates the tenacity of many social problems.

The obstacles to dealing effectively with such problems are several:

- *Problems are difficult to define.* The extent and severity of such problems are often unknown, the causes obscure and indirect, and boundaries of the problems diffuse and shifting. Efforts to define problems precisely enough to attack them may omit possible remedial alternates or neglect important social values.

- *Problems are imbedded in a complex system.* Problems are closely interrelated, making it difficult to treat one effectively without treating the whole or without adversely affecting connected problems. These interdependencies strain the capacity of social institutions, whose vitality and scope may be less than the force and breadth of the problems themselves.

- *Problems may be heightened by other developments.* Rapid changes of almost any kind may produce at least temporary disruptions in a system which is so tightly interconnected. Increasing population and urbanization are but two factors which intensify already existing strains.

- *Possible resolutions may threaten values and vested interests.* Potential approaches to alleviating social problems may conflict with deeply held beliefs, especially if they involve the redistribution of political, economic, and social power.

- *Inadequate knowledge impedes action.* The necessary knowledge for predicting the individual and social reactions to public policies or actions does not yet exist.

These are only a few of the obstacles in meeting the social challenges. The tasks which these problems pose for science are immense. Although they involve the whole of science, the tasks apply particularly to the least developed of the disciplines—the behavioral and social sciences. These disciplines need to be significantly strengthened, in both their basic and applied aspects, if the Nation is to respond more successfully to its social problems. Although knowledge alone does not guarantee success, its lack almost certainly reduces the chance and extent of progress.

The prime deficiencies of the knowledge base are inadequate information on the current state of society and lack of detailed data about particular individual and social problems. The expansion of effort in the social indicators area, as well as in large survey research, is essential for correcting these deficiencies. A related requirement is improved methods for gathering data and for analyzing and synthesizing the findings in forms relevant to social action. The significance of scientific information is that it can provide evidence for needed social change as well as suggest courses of action. Such information, if definitive, can be used to counter inertia or "vested interests," which are frequently the chief obstacles to social reform. Finally, and most fundamental, is the need for general, comprehensive theories of the individual and of the structure and dynamics of social systems. No such broad theories now exist that are based upon data, except in the field of economics. Such theories are necessary to:

(a) predict the consequences of proposed policies,
(b) provide guidance for collecting data relevant to possible policies and problem areas, and
(c) provide confidence to the general public and officials of the necessity and wisdom of the action, in order to generate the political will for implementing the proposed policies.

Efforts to develop the necessary knowledge—in data and theory—may encounter some peculiar difficulties. The knowledge gained may remain valid for only a relatively short period of time, because of the incessant change which people and social institutions undergo. There is, in addition, the possibility that the objects of study may be modified by the very act of studying them. These essentially methodological problems may be solved, but they do suggest that until that time the general propositions of the social sciences may lack the immutability that is usually associated with laws in the natural sciences.

The natural and social sciences differ in another important way. Both observation and experiments are used as methods of research in the natural sciences whereas observation alone is the primary method of the social sciences. The limited use of experimental methods seriously impedes development of the social sciences. Although there often are constraints against their use, increased efforts should be made to find acceptable forms of experimentation in social areas. A start in this direction is illustrated by recent experiments in education financing and income maintenance, which were designed to test the feasibility of approaches to these problems prior to legislative action.

Challenges of Man's Increasing Power

Over the past 100 years man's ability to modify, even irreversibly, the worldwide habitat has grown enormously. This is due partly to simple increase in numbers—the population explosion—but also to growing technological capabilities. Challenges of this type are the prime concern of this report.

Compared with the other types, these challenges are less familiar and often lead either to exaggerated fears or to complacency—to panic response or to irresponsible inertia. Such responses frequently arise from the lack of knowledge. The sparse evidence available admits of many different interpretations, biased by different political predilections or social values, and the distinction between fact and value becomes more blurred the more inadequate the understanding.

In a fuller sense, though, clear and adequate description of these emerging problems is exceedingly difficult. First, "simple" trend extensions do not foretell what is going to happen. Indeed, the incompatibility of different trends assures that they cannot all continue. Thus, simple extension of current trends shows an impossible future—not a likely one. The real difficulty in foreseeing the future is in perceiving which trends will change, when, and how, and what trends now so insignificant in magnitude as to be barely perceptible will grow into the major influencing factors in the future. It is these latter factors that are the storm signals of the future, and that require extensive knowledge of the multitude of related factors and a deep understanding of their interactions. The requisite knowledge and understanding are frequently unavailable.

A second difficulty is the growing interrelatedness of these problems. Population growth, food production, energy demands, mineral resources, environmental pollution, for example, are not independent problems. Because of these interdependencies, it is increasingly difficult to find solutions to one problem that do not aggravate another or create a new problem. The requirement of emission controls on automobiles which increase fuel consumption, the banning of phosphate detergents in favor of caustics which are hazardous to children, and the substitution of pesticides for DDT which are less damaging to birds but more harmful to humans illustrate this difficulty. One of the most striking characteristics of the future probably lies in its increasing interdependencies.

There is a final difficulty. Most of the problems that can be foreseen have so far shown only a small part of themselves. Popular attention and governmental concern tend to focus on these current manifestations of problems—even though they are often little more than precursive symptoms—with the result that actions intended as remedial are often halfway measures. An illustration of this is the use of catalysts in conjunction with the internal combustion engine, rather than the development of a new type of engine that would be intrinsically nonpolluting. Efforts that deal with symptoms often leave the underlying problems misunderstood or neglected, and may even be counterproductive. It is this—the response to symptoms—that gives the impression of moving from crises to crises, each more unexpected than the last.

II

CHALLENGE OF MAN'S POWER

Several of the growing problems presented by man's increasing power will be discussed in this section. The purpose is not, however, to suggest that these problems are well understood. The aim, instead, is to delineate some of the many inadequacies of current scientific understanding—deficiencies which prevent discerning interpretation of the problems and viable options for resolving them.

Population and Health

The "population" problem is broad in scope, ranging from the explosive growth in the number of people to matters of nutrition and health and to the question of the ultimate "carrying capacity" of the finite planet. The boundaries of the problem are diffuse and transitory, changing as new knowledge reveals new problems, new possibilities, and unexpected ramifications.

No single factor is likely to have so pervasive an effect on the character and quality of life as the total number of human beings. "It took all of history to the year 1850 to produce a world population of one billion; it took only 100 years for the second billion, and 30 for the third; it is taking only about 15 years for the fourth and it will take less than 10 years for the fifth billion. What these striking figures indicate is that the world cannot sustain such a growth for very long."[1] Indeed, the belief is growing that the world population has now reached a level at which further increases—especially rapid increases such as at present—will seriously impair the quality of life for all.

Yet even if the birth rate, worldwide, were to decline next year to the replacement rate of only two children per couple, world population would level off eventually at about 50 percent above what it is now, due to the age distribution of the present population. If zero

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[1] S. J. Segal, "Population Growth: Challenge to Science," in *The Greatest Adventure: Basic Research That Shapes Our Lives,* Kone and Jordan (eds.), The Rockefeller University Press, 1974.

population growth were achieved within the next 15 years, the ultimate world population would be 2.5 to 3.0 times larger than present. Thus, efforts to stabilize population size must reckon with long lead times during which the population would continue to grow.

The current growth rate in population is caused more by a decline in gross death rate than by an increase in birth rates, although both have occurred. That decline, in turn, is attributable to improvements in public health methods (water sanitation, nutritional programs, vaccines, for example), as well as higher living standards and the disappearance of some of the agents of disease and death. The continuing growth in population size underlies many problems and exacerbates almost all others, in many developing countries and increasingly in the industrialized world. It particularly frustrates the goal of elevating living standards in the developing world, a goal which seems largely obviated by projections of a doubling of the present world population by the turn of the century. The greater portion of this increase in population will come from the developing nations, where the rate of growth is some 2.5 percent a year as compared with 1 percent in the industrialized countries. This will intensify even more the urgent need for greater supplies of food for the very countries least able to expand their production.

Reduction in the growth of population, and perhaps its stabilization, appears imperative if developing nations are to attain—and developed nations are to maintain—a level of material existence which provides adequate education, health, and social welfare for all people. A crucial element in the control of population is the desire of individuals to regulate the size of their families. The translation of this desire into actual population control appears to depend upon economic and social incentives for limiting family size. Incentives prevailing in many countries, however, favor the large family. Although it is evident—from the experiences of this country and others—that family planning can be practiced effectively with present contraceptive techniques, fertility control measures which are simpler, more reliable, and cheaper are needed.

A world which so sanctifies human life as to limit the growth of its numbers will demand not only a better standard of living but also improvement in the health of its people. Indeed, if families are not assured that their offspring will be born healthy and remain so, prospects for limiting family size may be correspondingly diminished. For much of the world, health is still conditioned by two primitive factors: nutrition and protection from parasites. In the tropical belt many people suffer from inadequate nutrition, especially insufficient protein. Malnutrition results primarily from inadequate food production and deficient distribution due to the lack of purchasing power of the poorest fraction of the population. It sometimes results, however, from social customs leading to dietary habits that are nutritionally inadequate. Thus, while malnutrition is most prevalent in poor countries, it is by no means absent in rich nations, even among the most affluent of the population.

Although remote from current experience in our own country, the problems of parasitic infestation remain large in many parts of the world. Schistosomiasis claims millions of lives annually and debilitates many more; no effective means of control is yet in use. Malaria remains a major health problem despite spectacular gains. The primary method of controlling this disease at present involves the use of pesticides, chiefly DDT. Although use of DDT on the scale required to combat malaria may not represent a serious environmental hazard, other means of control that are inexpensive and ecologically safe are needed. These are only two of the many parasite-induced diseases found in much of the developing·world.

In more affluent nations the problems of malnutrition and parasitic infection are diminishing, along with numerous other classical afflictions, endocrine disorders, most bacterial infections, some insect-borne diseases, and those viral diseases now preventable by immunization. These achievements have come from advances in the biological sciences over the last few decades. In the place of these diseases, man is now confronted with two general categories of major afflictions: those loosely classed as degenerative disorders, including cancer, and those of genetic origin. Degenerative disorders now dominate medical practice in much of the developed world. They account for the bulk of the $80 million of annual expenditure for health care in the United States, much of which goes for "halfway medical technologies" capable of managing the diseases to some extent, but not of preventing or curing them.

The second general category of disease—diseases of genetic origin—are now growing in relative importance. Three decades ago, only a dozen or so genetic disorders had been identified; today the list is nearer to a thousand, including some 150 diseases in which the specific nature of the genetic defect is known. The identification of these many genetic disorders was made possible by advances in scientific and medical knowledge. Now that they have been identified, means for treating them must be sought. This illustrates how advances in scientific understanding lead to rising expectations and aspirations.

At present, nongenetic therapy is the most common mode of treating these diseases, an approach which results in the further dissemination of the defective genes in the population at large. Diabetes is a case in point. Before the advent of insulin, juvenile diabetics seldom lived long enough to reproduce, but since insulin therapy became available 50 years ago, many survive and reproduce, thereby transmitting the defective genes and increasing the incidence of diabetes. If similar approaches are used for other genetic disorders (e.g., sickle cell anemia and phenylketonuria), the result, although intrinsically desirable with respect to protecting the individual life, could become a growing public health problem for the general population.

These many diverse but related problems of "population" call for a correspondingly diverse set of responses from science and technology. Population control may be enhanced by better understanding of the personal, social, and economic motivations for large families, as well as by more knowledge of the chemistry and physiology of reproduction and its translation into new chemical approaches to birth control. In the area of nutrition, opportunities exist for raising the protein content of foods in tropical and semitropical lands through such means as genetic engineering of cereals, development of synthetic protein for enriching the diet, and greater production of fish protein through the use of aquaculture. In the case of degenerative and genetic disorders, much more knowledge is needed of the fundamental aspects of cellular and multicellular life, regardless of the particular disease of concern. This requires basic advances in the biological sciences which depend, in part, on continued stimulation from related disciplines, most notably chemistry and physics.

Problems of health, like problems of population control, are ethical-social-economic-biological problems. Efforts to cope with them must be guided by advancing insights across the full spectrum of dimensions.

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Primary Productivity

Only two of the many important aspects of this problem have been selected for discussion here: world food supply and demand and the maintenance of natural ecosystems.

The term "primary productivity" refers to the process by which plants utilize sunlight for the synthesis of organic materials. It is this process that supports the life of all the biosphere. Primary productivity by green plants supplies food, fuel, and fiber (cotton, lumber, and pulp) as well as ecosystems of great diversity. The vegetated surface of the Earth, in addition, receives wastes, cools the atmosphere, and helps to maintain the soil in a productive state. Plants supply the bulk of human food, primarily in the form of cereals which are consumed directly, or indirectly through animals that feed on grain. It has been estimated that two-thirds of the cultivated cropland is planted with cereals and that more than 50 percent of our direct energy intake comes from grain such as rice and wheat.

Food production has increased enormously during this century. Although the increase in land devoted to crops accounts for much of the growth, science and technology have contributed in major ways. Selective breeding, based on genetics, has resulted in highly productive new breeds. The mechanization of agriculture has raised productivity substantially. Irrigation has played a significant role by making possible and profitable the cultivation of areas otherwise unusable or marginally productive. The extensive use of chemical fertilizers—which has been estimated to account for at least a fourth of the total food supply—can triple or quadruple the productivity of soils when used in conjunction with other inputs and appropriate practices. Finally, the chemical control of diseases, insects, and weeds has helped greatly in reaching the present high level of food production.

Despite these gains, it is increasingly difficult to meet the growing world demand for food. The present mismatch between food supply and demand has many signs: the recent abrupt decrease in food supplies at a time of increasing demand; massive purchases of grain on the world market, such as the Soviet Union's large purchase of wheat from the United States and China's from Canada; depletion of grain reserves; rapidly rising food prices around the world; and, most distressing, starvation among the peoples of sub-Sahara Africa and some areas of Asia.

The causes of the disparity between supply and demand are numerous. Bad weather in many parts of the world in recent years reduced the level of food production. Cutbacks in the acreage devoted to wheat were made by the major grain exporting countries (Australia, Canada, and the United States) in the late 1960's and early 1970's in an effort to maintain price levels. Grain reserves in North America, long used to redress shortages occurring elsewhere, were allowed to decline in order to meet the growing demand. The supply problem was worsened also by the decline in the world's fish catch, the most mysterious element of which was the temporary disappearance of anchovetta off the Peruvian coast—a source of 20 percent of the entire world catch of fish.

Two factors, both of a long-term nature, figure prominently in present and future relationships between supply and demand: continuing population growth and the rising demand for more food of higher quality, primarily animal protein, in Europe, Japan, and the USSR.

Although food production has advanced rapidly, so has population. The growth in food production has been roughly the same in developed and poor countries for many years, but the more rapid growth of population in the poor nations has absorbed virtually all their gains in food production. As a result, two-thirds of mankind is hungry and malnourished much of the time. Continued population growth, increasing costs of energy for agricultural production, shortage of fertilizer and its three-fold price increase, and rampant inflation, make the prospects bleak for the developing world to acquire the food needed to stave off starvation in the years ahead.

Nations with high and rising *per capita* incomes—particularly in Europe and Japan—are turning away from rice and wheat staples and increasing their consumption of animal protein. The high demand for meat in affluent countries reduces the grain available for direct consumption in the rest of the world. The substitution of meat for cereals, moreover, is an inefficient pattern of consumption: as a rule, seven pounds of grain are needed to produce one pound of beef, four pounds to produce one pound of pork, and three pounds for one of poultry. An additional cost of the substitution is an increasing incidence of degenerative diseases associated with animal protein and high fat diets.

Food production can be expected to increase in response to growing demand. Land suitable for crops, but held out of production, can be turned to agriculture. Over 55 million acres of such land was made available in the United States between 1972-74 for the planting of wheat, corn, and other grains. Less suitable land throughout the world can be converted to agriculture, although the costs and often limited availability of inputs (e.g., water, energy, and fertilizers) as well as environmental damage ultimately constrain such expansion. But perhaps the greatest potential for increased production lies in tropical agriculture. These regions, which offer the possibility of multiple annual crops, have only a small fraction of their land under cultivation. Moreover, they include countries which have the most critical shortages of food and the least ability to purchase it elsewhere. Tropical regions, however, are believed to have a delicate ecological balance, which may restrict food production to relatively low levels. Determination of possible ecological constraints is an urgent matter which should precede large efforts aimed at expanding production in these regions.

Further gains in productivity can be achieved through the wider application of modern agricultural technologies: mechanization, irrigation, fertilization, and control of weeds and insects. Each of these, however, has unwanted side effects or calls for expensive energy inputs. Mechanized agriculture, for example, requires expenditures of energy that may be far greater than the energy embodied in the food produced. Irrigation may raise the water table to such an extent that the growth of plants is eventually inhibited by waterlog or by salt deposits that develop just beneath the surface soil.

This situation has developed in West Pakistan where extensive irrigation has been used. Chemical fertilizers produce various hazards, such as the pollution of drinking water and the eutrophication of bodies of fresh water. The chemical control of insects and weeds, through the use of DDT and other chlorinated hydrocarbons, threatens many species of animal life.

Such costs and impacts as these may inhibit the spread of the "green revolution"—the application of high yield seed strains and modern technologies. This prospect arises from the fact that the new strains have high yields largely because they respond well to fertilizer, irrigation water, and pesticides.

Scientific research may yield means for overcoming several of these problems and side effects. Research in genetics may lead to plant strains that grow well in saline soils. Better understanding of nitrogen fixation could provide the basis for enhancing natural fixation processes and thereby lessen the dependence on chemical fertilizers. Similarly, new approaches to controlling pests—such as rapidly degradable pesticides or biological control, as exemplified by the mass sterilization of screwworm flies—can reduce significantly the need for the older forms of chemical control. Beyond this, research may provide means for enhancing agricultural productivity in several ways, ranging from methods of accelerating the photosynthesis process to the growth of plants in a liquid nutrient rather than in soil.

Whether the world food situation improves or worsens in the years ahead depends upon many factors such as: population growth, global climate, demand for animal protein, availability and cost of agricultural inputs, economic incentives for food production, and advances in science and technology. Since the future course of these factors cannot be foreseen, it is not known if the world faces a chronic food supply problem or a state of temporary shortages which will ease in the coming years. Population growth at current rates, however, will continue to exert immense pressures on the food production capability of the world.

In developing his agricultural system, man has selected a few plants with which he has achieved high productivity through extensive cultivation. This has led to a high degree of dependence on "monocultures" as the prime source of food. The long-term instability of intensive monoculture as practiced in the United States and elsewhere has become evident in the increased susceptibility to insect pests and pathogens. Cotton culture had to be abandoned in several areas of this continent because insects feeding on the plant developed resistance to all pesticides. The vulnerability of certain high-yield strains of plants used in monoculture was demonstrated in the summer of 1970 by the billion dollar loss of corn to blight, which occurred in large areas of the United States. Intensive monocultures, furthermore, are vulnerable to small climatic changes and heavily dependent upon fossil fuel for fertilizer, farm machinery, and irrigation. The decreasing availability and increasing cost of such fuels threaten the current level of high productivity.

This concentration on intensive monocultures has reduced significantly the diversity of the ecology. It has brought many species to extinction and reduced the variety of natural ecosystems. To counter this continuing trend toward monocultures, diversified "gene pools" must be established and maintained. Critical to future needs, particularly to needs which cannot be readily predicted, is a great variety of genetic stock among species of plants and animals. Yet the tendency has been to ignore many of the food stocks of primitive societies and to destroy vast regions of natural ecosystems which contain a desirable degree of organic diversity. The accelerating destruction of tropical ecosystems is an example of this trend.

Natural or seminatural ecosystems are essential for an industrialized civilization which consumes enormous amounts of energy and materials and ejects the spent by-products, wastes, and pollutants into the environment. Living ecosystems are needed to assimilate these by-products and to regenerate the essential properties of the physical world.

The research needs in this vast area are much too numerous to cite more than a small fraction of the major requirements. Better understanding is needed of the processes of primary productivity and the complex web of organic and inorganic interactions evolved from it. This includes greater knowledge of the fundamental physiological and ecological processes by which plants function within their habitats. Understanding is lacking of how these events are coupled into the complex biochemistry of metabolism within the plant. Such insight is essential to better crop production and is necessary for understanding such fundamental ecological phenomena as plant adaptation, distribution, succession, competition, and production within ecosystems.

Further research is needed to understand better the nitrogen fixation process and the role played by bacteria and fungi. Improved knowledge in this area is required to find natural operating nitrogen fixation processes that would reduce the need for chemical fertilizers.

Advances in genetics are needed to enhance the genetic manipulation and breeding of improved plant and animal species, as well as to develop and maintain gene pools. Enhanced crop yield, heightened disease resistance, improved protein content, increased utilization efficiency of soil nutrient and water supply are all possible through genetic selection. Such selection may be accomplished to a degree by traditional breeding, but greater success may result from such newly developed techniques as tissue culture transformation, somatic hybridization, or other as yet undiscovered methods.

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Energy

There is little need in these times to call attention to the problem of energy. It is mentioned here simply to illustrate the nature of the problem, how it arose and the likely future prospects, the interrelatedness of energy and other problems, and the general role of science and technology in the energy area. (The implications of the energy problem for basic research and technology are discussed in more detail in the next chapter.)

The energy problem of 1973-74 has been emerging over the last few decades: consumption of energy rose rapidly; major reliance was placed increasingly on one form of energy (petroleum); and the supply of this energy shifted from domestic to foreign sources. Ample warning had been given of the likely consequences of this combination of trends. But possibly the problem was too complex, too vast in scope, and too distant on the time horizon for the capacity of the institutions which are responsible for dealing with it. The bulk of the broader energy problem lies in the future. It remains to be seen whether recent events lead to a greater concern for the long-run future, or to a false confidence in the Nation's capability to cope with any crisis after it arises.

In past decades, energy has been cheap and abundant in the United States. It has recently become more expensive, and mismatches have occurred between available supplies and demand. These conditions became severe in the past year, only in part because of reductions in the supply of mid-East oil. While many factors underlie the problem, most are related to the phenomenal growth which has characterized petroleum consumption in the United States and, even more, in the rest of the developed world.

Accelerating strain on fossil fuel resources is the inevitable consequence of exponential growth in demand. Given anticipated growth rates in world energy consumption of three or four percent annually, and given current estimates of ultimately recoverable reserves, worldwide exhaustion of natural gas may be anticipated in this century, and of oil early in the next century. Even if present estimates of ultimately recoverable resources are unduly pessimistic, this will postpone the day of reckoning only a few decades, so long as demand continues its exponential growth.

The Nation could obviously survive with lower rates of oil consumption. Why, then, have recent changes in supply and price been disruptive? A part of the answer is that, once accustomed to a certain level of consumption, that level becomes a "need." But a more important part of the answer is that the energy distribution system and the transportation and manufacturing structure are all closely connected and rather finely attuned to each other and to current patterns of international trade. Sudden, major changes disrupt the system, and a long time period is required for adjustment. During this period, the supply of energy may oscillate between shortages and surpluses and prices may rise and fall, as efforts are made to alter the overall system so that energy supply and demand can be brought into balance. Problems of this sort will tend to recur in such systems unless adjustment times can be shortened, or capabilities to anticipate are improved, or redundancies or cushions are built into the systems. Since many of the disruptions are political in origin, and cannot be fully anticipated, redundancy among alternative energy sources and greater storage capacity would appear necessary as insurance. For these several reasons, "energy" is likely to remain a serious matter for many years; only the aspects of concern will change.

The energy problem illustrates the increasing interrelatedness of different problems. The demand for energy imposed by the world's increasing need for food has already been noted. The demand for energy to obtain, to reclaim, and to process mineral resources is also part of the total energy problem. The design of human settlement patterns—the design of cities and of the living and working environments—will have great effect, for better or worse, on energy consumption. In turn, the availability and cost of energy will have a profound effect on the future evolution of patterns of production and settlement. And of course, the processes of obtaining fuel, of transporting it, of generating electric power, of energizing the transportation system and industrial plants—all constitute a major part of the growing "environmental" problem.

The different roles that science plays in relation to the short-run and long-run aspects of problems are well illustrated by the energy area. In the short run it must be largely policy adjustments, rather than new technological developments or basic economic or social changes, that help cope with such problems. In the longer run, technology, as well as economic and social changes, must provide acceptable solutions.

The role of basic science differs for the different time periods. In the short run, science must assist in the recognition and interpretation of the problems, assessment of the available policy options, and evaluation of the risks and likely results of the various choices available. In the long run, its role is to provide the basis for new options. In the short run, only the established fund of knowledge—the results of basic research already completed—can help. In the long run, additional basic research can expand the fund of knowledge and overcome present inadequacies of understanding. These deficiencies can prove costly in the interim. Some costly examples at present are the insufficiency of reliable knowledge concerning the health effects of air pollutants, limited understanding of the behavior of materials under irradiation (which inhibits nuclear energy development), limited research on reactor safety, limited knowledge with which to develop alternatives to the internal combustion engine, and limited geological knowledge concerning the amounts and locations of fuel and mineral reserves in relatively unexplored areas.

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Minerals

The problems known collectively as the "energy problem" have a developing parallel in the minerals area. Trends in the use and supply of nonfuel minerals closely parallel those existing at the time the "energy problem" became generally recognized: increasing U.S. dependence on foreign sources of supply, rapidly growing worldwide demand for available supplies, and rising prices.

The U.S. is almost entirely dependent on foreign sources for such critical minerals as asbestos, chromium, diamonds, manganese, mercury, nickel, and tin while importing a large fraction of its needs for others such as bauxite, copper, gypsum, potash, platinum, and zinc. These and other minerals are a main source of metals and nonmetals for machinery, chemicals, fertilizers, construction materials, communications systems, and various consumer goods. An adequate supply of minerals is indispensable to an industrialized society.

The accelerating problem of nonfuel minerals arises from increasing worldwide demand. Even if the current rate of growth in world mineral consumption leveled off, the anticipated demand for many minerals between now and the end of the century would require as much total production as in all previous history. Total mineral consumption has reached such high levels that the supply problems are not limited just to the United States. Even if the United States were to reduce its consumption—and possibly its economic growth in consequence—foreign demand for minerals will continue to rise. In any event, the United States in the future will either import less minerals or pay considerably more for them—and probably both.

The measures needed to avoid severe dislocations arising from mineral shortages include substitution, conservation, and recycling. Such measures emphasize the inseparability of the mineral, energy, and environment problems. The recovery of metals and nonmetals from ores and manufactured products requires energy; recycling and substitution help to save both energy and natural resources, and may improve the quality of the environment; recycling of metals usually requires less energy than the recovery of the same metals from their natural ores; and treating pollution leads, in many cases, to the recovery of valuable materials as well as to reduced environmental damage.

Recent scientific prospecting on land, based on predictive geology and geophysics, has led to the discovery of several new mineral deposits, such as copper in Arizona and lead in Missouri. In addition, remote sensing—recently given a new dimension by the data returned from NASA's ERTS-1 satellite—is pinpointing new target areas around the world for minerals exploration.

Geological exploration and research continue to identify potential new sources of scarce minerals. Recent deep-sea explorations suggest that the "manganese nodule" beds on the sea floor may represent an extensive supply of manganese, copper, nickel, and cobalt. In addition to the sea's long-recognized supplies of phosphates for fertilizer, deposits of iron, copper, zinc, nickel, and cobalt are being located.

Several major advances in the earth sciences over the last 15 years have led to a greatly improved knowledge of geological processes, which should contribute to understanding how and where ore deposits form and thereby enhance the ability to predict the location of concealed resources. Collectively, these new insights indicate that useful ores are found where geophysical and geochemical processes take place over sufficient periods of time and under sufficiently extreme physical conditions to permit adequate differentiation and concentration of minerals to occur. Certain continental margins are likely areas for such conditions to have existed.

Very little, however, is known yet about the internal processes involved; much further research is required to clarify them. It appears that crustal plates, when approaching the continents, make a downward plunge and thrust up kilometers-thick oceanic sediment. These sediments are metamorphosed and transformed into the continental rock that lies above. With more detailed exploration of these margins and a better understanding of the chemical and physical processes that take place within them, important ore bodies can probably be located. These continuing advances in knowledge improve the prospects of a long-term supply of important mineral resources.

While these advances are promising, other efforts need to be expanded. Scientific research—particularly in fields of the earth sciences such as geology, geochemistry, and geophysics—should be accelerated in order to understand better how ore deposits are formed and to improve techniques for finding them. Increased geological exploration and advances in technology can help to locate concealed deposits and make profitable the recovery of lower grade ores. New technologies can reduce the demand for minerals by developing methods for recycling current resources and substituting for less available materials. Such efforts in science and technology, both in research and in the number of experts trained, have been deficient in the past. The widening dimensions of the "minerals problem" calls for immediate expansion of these efforts.

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Weather and Climate

This subject, like others discussed in the report, has more facets than can be properly treated here. Two, however, merit particular attention: intentional modification of weather and inadvertent alteration of climate. The global importance of these facets, combined with the increasing prospect of human intervention in each, make both of them matters for concern.

The capability of modifying various severe weather conditions by "cloud seeding" has been demonstrated in several experiments. Seeding, for example, appears to reduce the high winds of hurricanes, thereby lessening their destructiveness. Hurricane Agnes in 1972 provides a vivid illustration of the damage that can be caused by such storms. Although Agnes was predicted several days in advance and the movement closely monitored and widely reported, the hurricane still caused some 120 deaths and $3.5 billion in property damage. On a much more tragic scale was the tropical storm which devastated Bangladesh in 1970, leaving at least 200,000 dead.

Cloud seeding technology, in addition, has proven effective in suppressing hail storms (which cause considerable damage to farm crops) and appears promising for reducing the damage from lightning. And the dispersal of "cold" fog by seeding has become a common operational technique at several airports.

A number of recent experiments appear to confirm that cloud seeding, under favorable meteorological conditions, can increase (or decrease) local rain or snowfall by a significant amount. The use of this capability is increasingly proposed as a means to relieve drought conditions and to help assure an adequate supply of water for agricultural, industrial, and municipal uses. Cloud seeding technology for these purposes, however, is still at an experimental stage. Before it can be employed on a practical basis, much more must be learned about the specific conditions under which a particular seeding treatment produces the desired cloud response. In addition, the impact of successful seeding in one region on the precipitation in adjacent and distant regions must be better understood. Furthermore, the seeding technology needs to be improved in order to provide for closer and more reliable control over the extent of the modification.

But the most perplexing problems involved in modifying the amount of rain and snow may not be scientific or technological. They center, instead, around the economic, political, and social implications of such weather modification. Unlike the mitigation of storms and severe weather, almost any change in precipitation is likely to be advantageous to some but harmful to others. Under these conditions, how are the disadvantaged groups to be compensated? Modification in one region may affect the precipitation in adjoining or even distant regions. How is it to be decided when and where weather is to be modified? These are only a few of the baffling issues that stand between the present limited capability for modifying weather and the realization of a system for managing precipitation.

While public attention has focused largely on intentional modification of weather, there is growing concern over the possibility of the inadvertent modification of climate. Specific examples of these concerns include the recent debate over the possible effects of the SST on the global atmosphere, impacts of the heat output from large power plants, and the effects of the higher temperatures and particulate emissions of cities on downwind rainfall.

Human activity may be involved on an even broader scale in changing the global climate. The growth and pattern of agricultural and industrial development over the last century may have influenced the mean temperature of the world. Warming temperatures prevailed for about 100 years, from the mid-19th to the mid-20th centuries, following the "little ice age" which lasted some 200 years. During the last 20-30 years, world temperature has fallen, irregularly at first but more sharply over the last decade.

The cause of the cooling trend is not known with certainty. But there is increasing concern that man himself may be implicated, not only in the recent cooling trend but also in the warming temperatures over the last century. According to this view, activities of the expanding human population—especially those involved with the burning of fossil fuels—raised the carbon dioxide content of the atmosphere, which acts as a "greenhouse" for retaining the heat radiated from the earth's surface. This, it is believed, may have produced the warming temperatures after the mid-19th century. But simultaneously, according to this view, growing industrialization and the spread of agriculture introduced increasing quantities of dust into the atmosphere which reduced the amount of solar radiation reaching the earth. By the middle of this century, the cooling effect of the dust particles more than compensated for the warming effect of the carbon dioxide, and world temperature began to fall.

The colder temperatures have been accompanied by marked changes in the circulation patterns of the atmosphere, which are prime determiners of weather. Several consequences of these recent climatic changes have been observed: midsummer frosts and record cold autumns in the midwest of the United States, shortening of the crop season in Great Britain, and the southward intrusion of sea-ice on the shores of Iceland. Possibly linked to these changes in temperature and circulation is the occurrence of an unusually large number of severe storms in many parts of the world, and the development of a calamitous drought belt extending around the world, passing through the sub-Sahara, Middle East, India, China's Yangtze Valley, and Central America.

The state of knowledge regarding climate and its changes is too limited to predict reliably whether the present, unanticipated cooling trend will continue, or to forecast probable changes in precipitation if the trend persists. The practical consequences of an extended cooling period—the effects on food production, energy consumption, and the location of human settlements—make it important to monitor climatic changes closely and widely, to determine their cause, particularly the role of human activities, and to seek countermeasures.

The atmospheric sciences have advanced considerably in the last 20 years, in part because of access to sophisticated devices and facilities developed for national defense and space purposes (e.g., high resolution and doppler radar, high altitude aircraft, and rocket and satellite observation platforms). One small indication of the progress is the current ability to make 48-hour weather forecasts that are comparable in quality to earlier 24-hour forecasts. While segments of the total weather and climate system are yielding to understanding, only in the most recent years has it been possible to begin studying the system as a whole. Even now, only the broadest limits can be placed on the magnitude of natural and man-made influences on weather and climate. There is probably less agreement now, for example, on the likely effects of carbon dioxide than there was a decade ago, when the complexity of the overall system was not yet appreciated. There is also lack of agreement as to whether the particulate content of the atmosphere is primarily the product of human activity in agriculture and industry or of natural causes such as volcanic dust.

Before such questions as these can be resolved, major advances must be made in understanding the chemistry and physics of the atmosphere and oceans, and in measuring and tracing particulates through the system. Comprehensive models which integrate the many interacting components of the system must be developed and tested. Advances in technology are needed for measuring and monitoring the system, as well as for ameliorating the deleterious effects of man and nature. Finally, greater understanding of the economic, legal, and social implications associated with changes in weather and climate are needed.

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Environment

Environmental problems arise from the interaction between man and his activities on the one hand and with resources, biota, and environments on the other. Managing the environment so as to maintain its viability, while satisfying human needs and aspirations, is an increasingly formidable challenge.

There is a great variety of extant and potential problems of local or temporary contamination of the environment. There are, in addition, two general sets of problems which are of considerable concern: irreversible entry of pollutants into the environment, and the determination of tolerable levels of environmental contaminants. Current knowledge is inadequate for dealing satisfactorily with either set of problems.

Some materials, either synthetic or naturally occurring, when dispersed in the environment are for all practical purposes irretrievable. Once in the environment, the materials may accumulate to harmful levels. One example of this is the heavy metals and fission products produced in nuclear reactors and in nuclear explosions. Another example of irreversible entry is the dispersion of solid small particles such as fly ash, asbestos, and talc into the atmosphere. If these particles are resistant to destruction, they become a part of the earth's surface solids and are reintroduced continuously into the atmosphere. The extant and potential effects of such atmospheric mixing are not yet known. Most of these particles are probably removed from the atmosphere by settling or in precipitation, but little is known about the threat posed to human health by the particles after they reach the earth's surface.

Asbestos particles illustrate this problem. They enter the atmosphere in a variety of ways: in mining the material, in building insulation, in the incineration of wastes, in the demolition of old buildings. Asbestosis, lung cancer, and mesothelioma afflict workers exposed to asbestos and even others less directly exposed, such as their families. These toxic properties have only recently been recognized, even though asbestos as a natural mineral has been used for centuries.

A second general set of problems concerns the determination of acceptable levels of pollutants in our surroundings. Most pollutants are naturally dispersed or removed, ultimately, from the environment. But they can reach local concentrations which endanger health, either because of accompanying unusual conditions (such as atmospheric inversions) or through long-term, low-level exposure. Pollutants occurring in this latter, more subtle, form may also produce undesirable alterations in the chemistry of the planet, its climate, and its complex ecologies. Compounding the problem is the possibility that new pollutants may grow to a dangerous level before their deleterious effects are detected. This is especially true when there is a long time lag between exposure and the subsequent appearance of a deleterious impact, e.g., in the case of aromatic amines and bladder cancer, a decade or more intervenes between exposure and appearance of lesions.

The rational determination of acceptable concentration levels of pollutants is a vexing problem—for society and science. "Safe" limits may be set which are more stringent than necessary, thus imposing excessive economic and social costs; on the other hand, if limits are set too liberally, the resulting damage—seen only in retrospect—to the environment and health may be great.

The current stock of knowledge regarding the environment is more descriptive than explanatory and predictive. Base line measurements are needed to gauge changes in the state of the environment, and improved analysis of ecological structure and process is required to forecast the environmental consequences of alternative policies and technologies. Two general approaches are available for expanding the stock of knowledge. The first consists of tracing pollutants through the environment in an effort to determine their sources, routes, rates, and fates, which helps to reveal the environmental interactions as well as the opportunities to prevent, control, or repair ecological damage. The second approach involves the response of ecosystems—their organisms, productivity, and structure—to perturbations that exceed the normal range of environmental change.

New approaches and improved research strategies are needed, especially for setting acceptable limits on pollutant levels associated with long-term, low-level exposure. One such approach is based on the possibility that changes in the community structure of land or marine organisms may yield clear and timely signals of harmful levels of pollutants in advance of chemical detection. The detection of chromosome aberration or changes in physiology in both higher and lower organisms may also be a useful approach. Several methodological problems must be overcome, however, before these and similar approaches can provide reliable, early-warning signals of impending threats.

It is clear that environmental problems are often not exclusively scientific in character, in that they involve human values and economic and social considerations, as well as scientific knowledge. The aesthetic value of wild landscapes or the desirability of urban open space illustrates this characteristic. Science can provide understanding and alternatives based on knowledge, but society must choose from among the alternatives based on the relative importance it attaches to the values affected.

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The Challenges in Perspective

The primeval challenge of the unknown and a multitude of challenges of the natural environment still confront us. Social problems, though greatly changed, still persist and in some ways have intensified in recent years. But it is the challenges created by man's increasing power to shape the future that are escalating most dramatically.

Because of the interdependencies characterizing the modern world and because of the rapid rates of change, challenges such as those outlined are becoming more difficult to cope with—difficult both for society at large and for the scientific community. Interdependencies strain the capacities of organizations and decision processes. Problems now cut across the organizational and jurisdictional boundaries that were more or less congruent with problems in the past. Informed decisions now require assessment of a multitude of ramifications and interactions, but the extensive knowledge and understanding needed for these assessments are not always available, nor are institutional incentives always present to encourage such assessments.

Rapid rates of change place additional burdens on organizations and decision processes. Rapid change, while diminishing the opportunity to look ahead, multiplies the knowledge required for reliable insights into the future. Rapid change also reduces the relevance of precedent, of custom, of traditional values, and of conventional wisdom as guides for decision. As the rate of change quickens, society's decisions and rules must either be continuously reformulated or else founded on deeper strata of knowledge and understanding. Otherwise, shifting circumstances will quickly erode their applicability, and they are likely to become part of the problem rather than the solution.

With slower rates of change, past answers are a better guide, and the occasionally needed revisions can be formulated, tested, and revised after problems are already upon us. With faster rates of change, problems need to be foreseen rather than experienced, and the consequences of policy choices need to be anticipated rather than discovered. The task of foreseeing problems and predicting policy outcomes is, however, immensely more difficult than the task of reacting to events and adjusting policies by trial and error. Of course, no amount of science or rational analysis can guarantee perfect foresight or the discovery of all possible options, but lack of perfection is no argument for failing to make the best possible use of the intellectual tools available, or for failing to take advantage of every opportunity to add to these tools.

Interdependencies and rapid change also strain the capacities of our current fund of scientific knowledge and our current research methodologies. The need is increasing for knowledge of the multitude of interdependent factors and processes involved in the changes, as well as for experimental and analytic methodology applicable to complex, unique, rapidly evolving systems, including social systems.

III

ADEQUACY OF SCIENCE TO MEET THE CHALLENGES: TWO ILLUSTRATIVE TESTS

In this chapter some of the major challenges discussed earlier are translated into the derived challenges posed for science. The adequacy of the existing base of scientific knowledge to meet these challenges is assessed, and gaps in this base, which must be filled in the future, are identified.

Science can provide objective understanding of the nature and dimensions of each such problem, and offer alternate approaches to its possible solution. The scientific knowledge base and the capacity to use it are necessary, but not sufficient, prerequisites for alleviating the large and complex problems noted in this report. To these must be added a viable and sustained level of societal commitment to solving the problems, expressed in appropriate fiscal, institutional, political, and social terms.

Each of these elements must be present in sufficient strength if challenges of the magnitude discussed herein are to be met successfully. Subsequent attention in this chapter, however, will focus on the essential scientific aspects.

For the purpose of assessing the adequacy of science to meet these challenges, two problems are selected as illustrations: "energy" and "cancer." These problems were selected as examples only; similar analyses could be made of each of the other challenges, and similar general findings probably would be obtained. The two examples, however, have certain desirable characteristics for the present purpose: "energy" and "cancer" represent quite different kinds of problems; the core scientific disciplines involved differ in the two cases, although some overlap exists among supporting disciplines; each problem satisfies, to some extent, the two societal criteria cited above for successfully meeting complex challenges; and both are the subject of recently initiated national programs aimed at responding to the challenges they represent.

Cancer

Some 50 million Americans living today will be afflicted with cancer and two-thirds of them will die from the disease, if present trends continue. One of every six deaths in the United States is now attributable to cancer, a toll that is exceeded only by deaths from cardiovascular diseases. Almost half of those who die from cancer are less than 65 years of age, with leukemia being the major disease killer of children under 15 years of age. The incidence of cancer and the mortality from it have increased steadily over the last 40 or so years for which statistics on the disease are available.

The Growing Science Base

During the same period remarkable progress was made in the understanding of living organisms. Within the overall advances in the biological sciences—to which chemistry and physics made major contributions—were many fundamental advances in biochemistry and its derivatives, such as immunochemistry, cellular genetics, cell biology, molecular biology, and virology. Progress in these areas expanded the knowledge of normal cells, providing new insights and greater understanding of their structure, functioning, and division. Most of this knowledge was acquired through basic research designed primarily to extend the realm of scientific understanding, rather than for its potential applications.

This understanding, however, provided the basis for elucidating differences between normal and cancerous cells, an essential step in determining the nature of cancer and in developing approaches for preventing and treating the disease. The resulting characterization of cancer is that of uncontrolled proliferation of malignant cells which fail to receive or respond to signals to halt further division. Instead of an orderly distribution of cells in the surrounding tissue, the spatial arrangement of malignant cells appears to be random or haphazard. And in contrast to the spread of normal cells, cancerous cells may become detached from a tumor and move to another site sometimes remote, where a new tumor is started.

Research over this period also provided insights into the factors which initiate cancer. There appears to be no single cause of the disease—or perhaps more properly, "diseases." Indeed, it is not yet clear whether cancer is a single disease that is manifested in various forms, or many diseases that exhibit similar symptoms. Many factors appear to play an influential role, including heredity and the individual's own metabolic, hormonal, and immunological responses. In addition, man's own acts may be involved in a causal way. Some 80-85 percent of all cancers are estimated to have an environmental cause, resulting from exposure to a variety of agents—chemicals, viruses, and ionizing radiation—many of which are man-made.

The various lines of research, which were undertaken primarily to further the understanding of normal biological processes, laid the basis for several therapeutic approaches to cancer. These included the use of chemicals (drugs) which interfered with or inhibited the continued growth of certain types of cancerous cells, as well as surgical and radiological techniques. These therapies, used singly and in combination, now permit a significant degree of success in treating several types of cancer—childhood leukemia, Hodgkin's disease, choriocarcinoma, skin cancer, prostate cancer, and cancer of the uterine cervix.

By the early 1970's, progress in the understanding of normal cell biology and in some approaches to chemotherapy seemed sufficient to convince some scientists that the stage had been set for a major, focused attack on cancer.

The National Cancer Program Plan

The elimination of cancer was announced as a national goal in 1971, and the National Cancer Institute was directed by the President to prepare a National Cancer Program Plan. Assisted by several hundred of the most knowledgeable scientists in the country, the Institute prepared a plan of effort which was published in 1973. The most salient of the several volumes comprising the Plan are "The Strategic Plan" and "Digest of Scientific Recommendations for the National Cancer Program Plan."

The ultimate goal of cancer research is the development of means for eliminating human cancer. Toward this end, the National Cancer Program Goal has been defined as follows:

> To develop, through research and development efforts, the means to significantly reduce the incidence of cancer and human morbidity and mortality from cancer by:
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> - preventing as many cancers as possible
> - curing patients who develop cancer
> - providing maximum palliation to patients not cured
> - rehabilitating treated patients to as nearly normal a state as possible.

The Program, it should be noted, is one of research and development, not of the delivery of health care. The ultimate alleviation of cancer is to be achieved through the application of research results by medical and public health practitioners, although a component of the Program is designed to hasten the practical application of results from the research program.

Toward the attainment of this Goal, a Program was devised which delineated seven major Objectives:

1. Develop the means to reduce the effectiveness of external agents for producing cancer.
2. Develop the means to modify individuals in order to minimize the risk of cancer development.
3. Develop the means to prevent transformation of normal cells to cells capable of forming cancer.
4. Develop the means to prevent progression of precancerous cells to cancer, the development of cancers from precancerous conditions, and spread of cancers from primary sites.
5. Develop the means to achieve an accurate assessment of (a) the risk of developing cancer in individuals and in population groups and (b) the presence, extent and probable course of existing cancers.
6. Develop the means to cure cancer patients and to control the progress of cancer.
7. Develop the means to improve the rehabilitation of cancer patients.

It is not the purpose of this report to assess whether, indeed, the stage had been set adequately for the major effort which this Plan entails. Nor is the purpose to assess the general structure of the Plan and its balance, or to comment on the relative resources which should be applied to the several program elements. The purpose, rather, is to emphasize the criticality of fundamental biological understanding to the success of the total endeavor.

Adequacy of the Current State of Basic Research

A successful and efficient attack on cancer—or on any of the problems discussed in this report—requires an adequate level of basic scientific knowledge. Such knowledge is necessary for understanding the nature of the problem, the etiology, dynamics, and symptoms of the disease(s). In the absence of this knowledge, the problem cannot be defined with sufficient precision to attack it. Basic knowledge is needed also to provide plausible approaches to the problem—directions of attack which can be implemented and which hold some promise of success. Without this degree of knowledge, any approach is perforce trial and error and must depend upon fortuitous events for its success. Lacking an adequate base of understanding, efforts to cope with cancer are likely to fail and are certain to waste valuable resources and precious time in the process.

Is the state of scientific knowledge regarding the nature of cancer adequate to develop an effective plan for ameliorating the disease? The fact that a program of research and development could be formulated at all suggests that the current knowledge base is sufficient for this purpose. Formulation of a detailed Plan was possible only because of the diverse clues obtained from earlier research.

The existence of crucial knowledge gaps is explicitly recognized in the Plan. Indeed, much of the planned effort consists of basic (non-targeted) research to extend the base of scientific knowledge. In this regard, "The Strategic Plan" states:

> Our areas of ignorance are still large, and caution must be exercised to assure that the total attack is well balanced between non-targeted and targeted research.

The pivotal role of basic research in achieving the Objectives of the Program is emphasized also in the "Digest of Scientific Recommendations for the National Cancer Program Plan":

> The very foundations of cell biology, molecular biology and immunology must be strengthened and the entire structure must be enlarged and possibly remodeled. . . .

Accordingly, several approaches to the attainment of each major Objective have been delineated and, within each approach, a large number of Approach Elements, i.e., highly specific defined subobjectives. To illustrate, Objective 3 above is to develop means to prevent transformation of normal cells to cells capable of forming cancers. The alternate approaches to that Objective are: (a) study the nature and modification of the precancerous state and determine mechanisms accounting for high degrees of stability of cell function; (b) delineate the nature and rate of oncogenic cell transformations in carcinogenesis (include aspects of cell culture and viruses); (c) investigate cellular and organismal modifiers of the transformation and promotion processes; (d) identify immunologic aspects of transformation; and (e) study cell surfaces and cell membranes.

The Approach Elements are numerous, as illustrated by the following random sampling of "elements" associated with Objective 3: to elucidate mechanisms of DNA replication and repair in normal and cancer cells; to characterize the molecular basis for development, stability, and inheritance of differentiated cells; to delineate the interaction of precancerous cells with their host; to delineate cancer genomes through manipulation of cells or chromosomes; to define the relationship of mutagenesis to carcinogenesis; to characterize molecular species involved in expression of cancer genomes; to extend studies on the biology, molecular biology, genetics, and enzymology of oncogenic viruses; to determine the role of hormones in cancer; to determine the role of nutrition in cancer; to define the genetic basis of the immune response; to study the composition, structure, and function of normal and cancer cell membranes; and to define the role of membrane antigens in tumor development and rejection.

The various and diverse Approaches outlined in the Plan share a common and important characteristic: the basic role of fundamental understanding of biological processes in attaining the Goal of the Program. Success is conditioned entirely upon gaining sufficient understanding of the normal life of a tissue cell, and the manner in which it is altered after the neoplastic transformation.

One of the largest gaps in modern biology is detailed knowledge about the mechanism of normal cell differentiation and the means by which such cells maintain their stability throughout life. The question of how normal cells acquire and maintain their differentiated character encompasses some of the most important unknowns in cell biology. The answer to this question—which will require much fundamental research—is essential to a successful attack on cancer.

Although clues abound, there is as yet no satisfactory description of the fundamental nature of the neoplastic transformation involved in cancer. Indeed, present knowledge is insufficient to assure that the structure or function which is altered in the course of that transformation has been properly described. Even if this critical information were available, a large effort would still be required to achieve the major Program Objectives, for success will require answers to most of the other questions posed.

If human cancers are caused by viruses—whether they invade from without or are carried in the genome from birth—it is not clear what those viruses actually do that results in malignancy. To repeat, it is difficult to understand how malignant cells escape from an otherwise normal organ, when understanding is lacking of what prevents normal cells from doing so. Plainly, since cancerous cells differentiate and undergo repeated divisions, they escape from some control mechanism. But the nature of the control mechanisms operative in the normal cell itself is totally unknown.

On the surface of cancer cells are macromolecules, known only by their immunological properties, which are not present on the surface of the normal cells from which the cancer cells developed. But the relationship, if any, between the presence of these macromolecules and the uncontrolled growth and diffusion of cancer cells is unknown at present. Whether the macromolecules (which are called "tumor antigens") are a primary aspect of neoplasia, or a secondary consequence, remains to be established. Their presence, however, furnishes another possible clue. It may be that the neoplastic transformation is not a rare event which inevitably leads to cancer but rather a frequent process which relatively rarely culminates in the disease. This could be the case if such transformed cells are usually destroyed by the normal immune system which recognizes the modified cells as "foreign," because of their new surface antigens. Were this the case, an important clue would lie in understanding why the immune system sometimes fails to recognize or destroy the foreign cell, thus permitting neoplasia.

These few details are offered not so much for the insight they afford into the nature of cancer, but rather to emphasize that, even now, attempts to deal with the disease are limited by the fact that the understanding of neoplasia is still at a primitive, descriptive level, limited by understanding of normal biology. Success in attaining the ultimate goals of the Plan depends upon gathering a sufficient body of information along the lines indicated by the numerous Approach Elements of the National Cancer Program Plan. The possibilities for early diagnosis, for prevention, or for definitive therapy could be markedly enhanced by such knowledge. But even then, considerable additional effort would remain before the Objectives of the Plan could be realized.

The translation of fundamental understanding into effective therapeutic approaches is a major goal of the Program. Current therapeutic approaches rest on empiricism and a rather general level of understanding. For example, radiation is known to be injurious to cells in mitosis; hence, dividing cancerous cells should be more susceptible to radiation than normal cells. Again, cell division requires synthesis of DNA, the genetic material in chromosomes; hence, chemicals which can interfere with DNA synthesis are candidates for use as anticancer drugs. But both radiation and such drugs have only limited usefulness because of their inefficiency and the fact that they damage normally dividing cells such as those of the bone marrow. What is required is a family of agents directed more closely at the processes involved in the neoplastic transformation. No such agent is available nor can the process in question be described. Even when that knowledge is in hand, the remaining task will be formidable. An illustration of the difficulty of this task may be drawn from another major disease: essential or malignant hypertension. It is now known that this disease, in many instances, is the consequence of an alteration in the kidney which results in liberation into the blood plasma of an enzyme, *renin.* This enzyme catalyzes the removal from a normal serum protein of a decapeptide, a linear chain of 10 amino acids of known composition. The terminal two amino acids of the decapeptide are removed by a second enzyme contained in normal blood plasma, yielding an octapeptide, a chain of eight amino acids called "angiotension II," the most powerful pressor agent known. If a drug were available which could inhibit either of the two enzymes involved in this process, it could serve as a definitive therapeutic agent for malignant hypertension. Unfortunately, no such inhibitor is known as yet. Alternatively, were there an otherwise innocuous compound which could mimic angiotension but not cause arteriolar constriction, it too could serve as the ideal antihypertensive drug. But efforts in this direction remain unsuccessful, and this disease remains a serious health problem. By analogy, if there is some parallel alteration in the chemical life of the cancerous cell, the way might be opened to an equivalent rational therapeutic approach. The need to look elsewhere for a persuasive example of a promising current approach to therapy underscores the current state of ignorance regarding the essential nature of cancer.

The broad sweep of the National Cancer Program Plan for advancing basic understanding requires contributions from many scientific fields. The biological sciences, of course, constitute the core disciplines, with a central role for biochemistry, cell biology, molecular biology, immunology, and oncology. Chemistry is also a key field of research ranging from the detection and analysis of air-borne carcinogens to the synthesis of new drugs. Mathematics will become increasingly important in "modeling" cancer which, in turn, means new uses of computers and perhaps the design of special purpose computers and associated languages. In addition to these individual disciplinary efforts, increasing numbers of engineers, statisticians, and epidemiologists are needed to work with biomedical research teams.

The involvement of a large part of the total spectrum of scientific disciplines is necessitated by the complexity of the cancer problem, the large gaps in essential knowledge, and the broad scope of the plan of attack. Comprehensive and concerted efforts to deal with any of the problems discussed previously in this report would require the contributions of a similarly large array of scientific disciplines. The only difference would lie in the relative mix of disciplines which must be marshaled.

Scientific Manpower Requirements

The National Cancer Program Plan calls for an operating level of approximately 13,500 professional research scientists,[1] with some 11,000 of these needed for the component of the National Program to be supported by the National Cancer Institute. This operating level is to be reached by fiscal year 1982, building from an estimated level of 5,500 scientists in fiscal year 1972.

The available scientific manpower (along with associated facilities and supporting resources) is a major constraint on the more rapid

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[1] A research scientist is defined as one holding an M.D. or Ph.D., or equivalent degree, who is responsible for the conduct and/or direction of particular research tasks.

expansion of the overall Cancer Program. As noted in "The Strategic Plan," to achieve the target operating level at this time "is not only impossible from the scientific standpoint but impractical and undesirable from the standpoint of impact on national biomedical resources." As the Program is steadily expanded, the required research scientists are to be drawn from the growing research manpower pool. In addition, training programs are planned for "filling specific critical scientific discipline deficiencies."

In spite of these measures, "a deficiency in the number of scientists may begin to occur in FY75 and may continue to increase as the program expands." This estimate applies to the total number of research scientists needed for the Program, and does not include the specific disciplines in which deficiencies are expected. Critical deficiencies, however, exist currently in the scientific areas of carcinogenesis, immunology, cancer biology, epidemiology, and pharmacology, according to a preliminary analysis presented in "The Strategic Plan."

Scientific manpower deficiencies, such as these, are likely to occur at the outset of any large, new effort involving research and development as a major component. These deficiencies, furthermore, are likely to persist for several years, unless existing programs employing the needed scientists are reduced, because of the long time period required for training scientists. Thus, the existing scientific manpower—and the time lag in expanding the supply—will generally act as a major constraint on the rate of growth of new R&D-intensive programs.

Prospects for the Cancer Program

The success of the National Cancer Program will depend directly upon the continuing progress of fundamental biological science. Success lies, more particularly, in reaching an understanding of the nature of a living normal cell and the alterations to which it is subject.

The basic research which must be done to achieve this understanding cannot be given more than broad, general direction. Given sufficient support and resources, the research must follow its own leads, the intellectual structure building upon the platform already constructed. It is of little consequence to society whether this very large area of fundamental biology is formally viewed and financially supported as "cancer research" or simply as "fundamental cellular biology." The same scientific community will be enlisted in the task, and those investigators who focus on "the nature of cancer" will continue to gather clues in the attempt to develop the understanding required so that the societal goals envisioned by the National Cancer Program Plan may one day be reached.

Energy

The pattern of energy use underlies, shapes, and reflects a culture. Few other factors impact so pervasively on human life. The forms, quantity, and cost of available energy determine the possible variety in human settlements; condition the economic and social structure of society; and influence the direction and rate of economic growth, level, and type of employment, forms of technology, methods of food production, and life styles. Thus, sudden and significant changes in the pattern of energy availability and use can be profoundly disruptive—nationally and internationally.

Consumption of energy on a worldwide basis has increased by some 6 percent annually for several years. This amounts to a doubling every 12 years of the quantity of energy consumed. For the United States, growth in consumption averaged 4.3 percent over the past decade, while rising to almost 5 percent in recent years. Growth rates for most other developed countries have far exceeded those of the United States in the last few years. Even so, the U.S. consumes a third of all energy used in the world, while having only 6 percent of its population. On a *per capita* basis, U.S. consumption is some six times that of the world average, with the difference between the United States and many developing nations being as much as a factor of 100.

While the U.S. rate of demand for energy rose to nearly 5 percent annually, domestic production grew at a steady rate of some 3 percent annually. The result was an increasing reliance on imports—primarily in the form of petroleum. In the first half of 1973, the United States imported 17 percent of its total energy consumption, including 33 percent of its petroleum. The chief suppliers of the imported energy were the Organization of Petroleum Exporting Countries (OPEC).

In the fall of 1973, these nations quadrupled the price of imported oil. It is estimated that, as a result of these higher prices, U.S. expenditures for foreign and domestic oil alone will rise by $26 billion in 1974. Furthermore, the same price increases are expected to add 2 precent to the U.S. inflation rate in 1974.

Preceding these developments by a few months was a directive from the President to the Chairman of the Atomic Energy Commission to "undertake an immediate review of Federal and private energy research and development activities. . .and to recommend an integrated energy research and development program for the Nation."

The National Energy Program

The report[2] presenting the recommended Energy Program for the Nation was presented to the President in December of 1973. Like the National Cancer Program Plan, the development of the National Energy Program was assisted by the advice of several hundred scientists, engineers, and technologists from all sectors.

The recommended Program, it should be noted, encompasses many aspects other than energy-related R&D such as economic, institutional, and legal considerations. The overall goals of the Program call for the Nation to "regain energy self-sufficiency by 1980" and to "maintain that self-sufficiency at minimal dollar, environmental, and social costs." The objective of the National Energy R&D Program is to assist in achieving these goals through research and development.

The major tasks "required to regain and sustain self-sufficiency" were identified as:

Task 1. Conserve energy by reducing consumption and conserve energy resources by increasing the technical efficiency of conversion processes.

Task 2. Increase domestic production of oil and natural gas as rapidly as possibie.

Task 3. Increase the use of coal, first to supplement and later to replace oil and natural gas.

Task 4. Expand the production of nuclear energy as rapidly as possible, first to supplement and later to replace fossil energy.

Task 5. Promote, to the maximum extent feasible, the use of renewable energy sources (hydro, geothermal, solar) and pursue the promise of fusion and central station solar power.

The National Energy R&D Program is to help accomplish these tasks. The specific technological objectives of the R&D program were defined in terms of three time periods as follows:

Near- Or Short-Term (Present to 1985)

This category includes research and development objectives that enhance the implementation of existing technologies, identify additional resources, and improve the

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[2] *The Nation's Energy Future*, a report to the President of the United States, U.S. Government Printing Office, Washington, D.C., 1973.

efficiency of existing techniques, practices, and processes. Particular attention is given to removing barriers to public acceptance, satisfying existing standards, and developing an improved basis for standards in all energy production and use areas.

Mid-Term Period (1986-2000)

Mid-term energy research and development program goals aim at providing alternative energy sources and increased ability to substitute more plentiful fuels for scarcer ones. Conservation and efficiency measures, conversion of coal to gas and oil, breeder reactors, and certain solar and geothermal sources are prime elements of the mid-term program.

Long-Term Period (Beyond Year 2000)

Many presently unanticipated variables, of course, will become important in the long-term period. Changes in the organization of society, in the patterns of transportation and other energy uses, in the needs of industry, and in overall economic growth patterns may occur. The long-term goal of the energy research and development program for self-sufficiency is the production of adequate amounts of environmentally clean, low-cost fuels from relatively inexhaustible domestic sources. Energy should be available in forms best suited to the energy needs of the various sectors of the economy.

In addition to these technological objectives, the Program specified certain supporting objectives:

- Enhance basic research into energy systems and fuel sources.
- Continue basic research into chemistry, physics, geology, and biology to identify new potentials and provide the basis of knowledge for solution of problems that experience shows will arise.
- Establish the nature, emission patterns, distribution in the environment, and ecological and medical effects of pollutants.
- Provide improved bases of knowledge for setting environmental standards and minimizing environmental impacts from energy technologies.
- Develop detailed methods to enhance environmental and ecological integrity and overcome any necessary but undesirable impacts that have accumulated.
- Create and sustain an adequate supply of scientifically and technically competent manpower to support the operation of the energy system and the research and development program.

Adequacy of the Current State of Basic Research

Fundamental research of the past provides a substantial foundation for planning and implementing the overall R&D program in energy. The results of such research, moreover, have provided the basis for several energy-related technologies that are now operational and constitute parts of the extant national energy system. Fission-energy technology and low-BTU gas conversion techniques are but two of the many areas in which basic research has had such a role. There are various other energy-related areas and technologies which require little if any additional basic research. These include surface and underground mining of coal and shale; coal and shale processing and combustion; oil and gas recovery; advanced air and nuclear ships transportation systems; and assessment of energy resources.

For several other areas, the science base is "moderately" adequate, but further basic research appears to be needed. These include oil-shale mining and reclamation; coal liquefaction; some energy-conversion techniques (e.g., high temperature gas turbines and use of waste heat); and some transportation systems (e.g., rail). In the case of coal liquefaction, for example, the development of reliable techniques depends upon vigorous research in catalysis, organic chemistry, sulfur chemistry, chemical kinetics, thermodynamics, and materials.

Significant advances in basic knowledge, however, are required in respect to certain energy technologies. Among these are the distribution and storage of energy; magnetohydrodynamics; geothermal energy; solar energy; and fusion energy. In regard to the latter, for example, fusion reactors depend on certain plasma behavior under conditions that have not yet been established in the laboratory.

The National Energy R&D Program Plan calls for substantial basic research in connection with each of the five major tasks cited above. The Program Goal of the basic research effort is:

> To explore basic phenomena, processes, and techniques in those physical, chemical, biological, environmental, and social sciences areas bearing on energy and to ensure the development of new basic knowledge in these areas.

Such research may often suggest new lines of development not contemplated at the time the overall program was first defined. Thus, if the technologies now sought should prove inadequate, the research may lead to other approaches having a greater probability of success. Basic research, therefore, increases the chances that present concepts and approaches will be developed successfully and, at the same time, provides a basis for new directions if needed.

The necessary basic research in energy-related areas covers a broad spectrum of disciplines and subjects: materials research, catalysis and chemical reaction kinetics, plasma research, chemical and physical processes, biological processes, physical environment and ecology, and social science research.

Materials Research—The inability to predict accurately the behavior of materials in extreme environments, and to design suitable materials, is one of the greatest technical obstacles to development and improvement of energy systems. There are various recognized gaps in fundamental understanding in these areas. One of these, for example, is reflected by the largely empirical approach which must be taken now in the search for superconducting materials with higher critical temperatures or easier formability. The steady advances made in solid state theory and in scientific instrumentation provide a firm basis for efforts to narrow these gaps and obtain new materials with properties required for energy-related functions. Some examples of areas of needed materials research are: (1) strength of materials, including embrittlement by hydrogen and radiation; (2) high temperature environments, including the impact of thermal shock, behavior of surface interactions, and microstructural changes; (3) radiation effects; (4) electrical conductivity, including superconductivity and conduction at high temperatures; and (5) refractory alloys, including their ductility, fabricability, and plastic and elastic properties.

Catalysis and Chemical Reaction Kinetics—Advances in these areas are critical to several approaches for producing energy, in terms of fuel production as well as the sequent processing of effluents. The use of catalysts can raise chemical reaction rates by as much as a factor of 10^8, and may often reduce or eliminate undesirable waste by-products in the process. Their use is expected to be significant in the processing of coal, oil and shale, and gaseous fuel production. Although catalysts have been used extensively, basic understanding is deficient in regard to how catalysts interact with reacting systems; this knowledge is needed to deal with the desulfurization problems of coal and heavy petroleum tars and crudes. Further knowledge of chemical reaction kinetics of noncatalytic systems is important in conserving existing fuels and in obtaining efficient uses of new ones. Some examples of important areas of study are: (1) structures of surfaces and absorbed molecules; (2) structure and immobilization of enzymes and soluble homogeneous catalyst molecules; and (3) mechanisms of homogeneous reactions including reactive intermediates.

Plasma Research—The behavior of plasma is not satisfactorily described by the methods used for studying solids, liquids, and gases. Considerable research, theoretical and experimental, must precede the development of plasma systems for generating and transforming energy—systems such as fusion reactors, magnetohydrodynamic converters, thermionic cells, high temperature chemical processing, and gas lasers. The needed knowledge centers around how to keep the plasma where it is wanted, how to keep it clean, and how to keep it hot.

Although much is known about certain aspects of the phenomena (e.g., effects of magnetic field shape, plasma density, and impurities), little is known about other facets such as the effects of rapid temperature changes as brought about by nuclear reactions, or the laws of scaling to large plasma volumes. Sophisticated experiments will be required in order to transform laboratory demonstrations into operational systems of energy production and conversion.

Chemical and Physical Processes—The basic processes of fuel preparation, combustion, and heat transfer are incompletely understood. Additional research is required if the efficiencies of these processes are to be increased. The results of such research would apply to the energy production functions performed at central stations: the chemical separation of impurities from fuel, such as sulfur from oil and coal gases; combustion of the fuel; and the transfer of the generated heat to the primary working fluid. The processes requiring study lie in the various disciplinary fields of physics, chemistry, and engineering, examples of which are separation chemistry, electrochemistry, fluid dynamics, energy transformation processes, heat and mass transport, atomic physics, nuclear properties and cross sections, thermodynamics, and combustion.

Biological Processes—The research required in this area centers around (1) energy conversion by biological means (conversion of cellulosic materials to fuels); (2) biological detoxification of effluents from energy systems; and (3) the determination of biological effects of toxic substances. Efforts in the first two of these can be expected to add to the basic energy supply and increase the conversion and use efficiency of various energy resources. Greater knowledge in the last area is essential for preventing hazardous health conditions and protecting the biosphere from toxic effluents of energy systems. Possible applications of such research range from the bioconversion of animal and plant wastes to usable fuels to the development of data for establishing standards for toxic substances release rates.

Physical Environment and Ecology—The physical environment, while providing energy resources, sites for energy system operations, and a repository for energy effluents, must be protected from assaults against its own vitality. To achieve this end, research is needed on (1) means for safely transporting and disposing of thermal and material loads; (2) ecological systems; (3) spatial and temporal distribution of trace substances; and (4) surficial faulting and rupture, seismology, and rock and soil mechanics. The knowledge acquired from such research can provide an informed basis for environmental control guidelines, standards, and legislation concerning energy conversion and use.

Social Science Research—Both basic and applied research in the social sciences are required, primarily in the disciplines of economics, social psychology, political science, demography, and mathematics related to these disciplines. The objectives of such research include: (1) improved economic theory and models relating energy use to other national parameters; (2) better knowledge of how life styles and the "quality of life" relate to national energy policy; (3) insights into the factors controlling population and economic growth; and (4) increased understanding of the Nation's international relationships and obligations in matters of energy.

As in the case of the National Cancer Program, basic research is required in a wide variety of scientific disciplines in order to meet the goals of the Energy Program. A part of the basic research program, as noted in the National Energy R&D Program, "is designed to find answers to questions now visible. Another part is intended as insurance against unknown future barriers to development progress. A very small part...is to encourage creativity and imagination along lines not yet chartable in the long-term concerns for renewable energy."

Scientific Manpower Requirements

It is anticipated that the Federal Program of Energy R&D would employ some 40,000 scientists, engineers, and technicians when the Program becomes fully operational. In 1973 about 50 percent of that number were employed in federally supported energy R&D. The Energy Program Plan notes that: "While the potential for redistribution of technical manpower is high, reorientation or retraining will be necessary, and major growth in the longer term must be ensured." Toward this end, the Program provides for manpower development. The first targets are (1) the expansion of educational faculty to train manpower for R&D in energy, and (2) the enhancement of the effectiveness of managerial personnel in government and industry for planning and implementing R&D projects. Subsequently, efforts will be directed to enlarging the base of energy-trained manpower through the support of students and expanding institutional capabilities to retrain and redirect technical manpower at all levels.

Manpower requirements in the private sector are substantially greater than those of the Federal Government. A "maximum effort" by industry to develop domestic fuel sources over the next decade is estimated to require 230,000 scientists and engineers by 1980 and 308,000 by 1985, compared with the employment of 141,000 in 1970.[3] (These estimates may be conservative in that they do not include the

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[3] *The Demand for Scientific and Technical Manpower in Selected Energy-Related Industries, 1970-85: A Methodology Applied to a Selected Scenario of Energy Output. A Summary,* National Planning Association, September 1974.

demand for scientists and engineers by industries supplying the energy sector.)

The demand for scientists in programs funded by the private sector is expected to increase to 61,000 in 1980 and to 83,000 in 1985, up from 40,000 in 1970. The largest increases between 1970-85 are expected for physicists (from 8,000 in 1970 to 22,800 in 1985), chemists (from 13,200 to 27,800), and mathematicians (from 7,500 to 13,900). The ". . .larger numbers of physicists and chemists [and mathematicians] will be required in the production of energy because of the increase in nuclear power plants;. . ."[4]

The requirement for engineers is expected to rise to 169,000 in 1980 and to 225,000 in 1985, as compared with 101,000 in 1970. Among engineers, the largest demand in 1985 is expected to be for electrical engineers (65,500 versus 25,600 in 1970), chemical engineers (51,500 versus 33,600), and mechanical (30,500 versus 8,000). These increases ". . .reflect changes in the energy production technologies in general and the rapid increase in the nuclear power generating units in particular."[4]

The future supply of scientists and engineers may be inadequate to meet the demands associated with increasing domestic energy production. However, the "supply situation will become considerably worse beyond the mid 1970's if current trends continue toward an overall decrease in the number of graduating physical scientists and engineers." "This already bleak future supply/demand relationship for the scientists and engineers. . .is further complicated by the fact that, in most cases, *experienced* scientists and engineers and/or those with skills beyond the bachelor's degree are needed."[4]

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[4] *The Demand for Scientific and Technical Manpower in Selected Energy-Related Industries, 1970-85: A Methodology Applied to a Selected Scenario of Energy Output. A Summary,* National Planning Association, September 1974.

IV

SUMMARY AND CONCLUSIONS

Challenges of Today and Tomorrow

This report reviews the challenges which have always confronted man—the unknown, threats from nature, and social conflict—and notes some of the ways in which science has helped to meet them. Principal attention, however, is focused on the new challenge posed by man's increasing power to shape the future, to modify, intentionally and unintentionally, the basic conditions of life.

Various facets of this challenge are discussed—population growth, food supply, energy demand, mineral resources, weather and climate modification, and environmental alteration—and major directions of scientific research needed to meet these problems are suggested. And finally, the adequacy of present scientific knowledge for coping with the many problems is tested against the needs in two specific areas—cancer and energy.

The problems, old and new, constitute a formidable challenge to this Nation and to the world. Many of the problems are likely to become even greater threats in the years ahead, possibly resulting in domestic turmoil and international strife.

The several problems coexist and are global in scope and implication. They are also closely coupled—changes in one modifying others. Because of these interconnections, it is difficult to attack the problems singly, and because of their global nature, the efforts of one country acting alone—rather than in concert with other nations—may not be effective in alleviating them.

The scope and depth of the problems, their coincidence and rapid growth, all underscore the sense of urgency with which these challenges must be confronted.

Role of Science and Technology

Science and technology, by themselves, cannot solve any of these complex problems. As part of a broader commitment and larger strategy, however, science and technology can play a pivotal role in helping to alleviate many of them. But these contributions will be neither immediate nor costless.

The principal role of science and technology is to provide more and better options than are now available for meeting the problems. Science can supply the basic knowledge required for understanding the origins and dynamics of the problems, for measuring their magnitudes and directions, and for devising and assessing possible approaches for coping with them. And technology, drawing upon scientific knowledge, can provide many of the practical tools and techniques for attacking the problems.

Together, science and technology provide the means for:

- Understanding and measuring human needs for energy; determining their trends and trade-offs; developing policies and technologies for efficient energy use; assessing the availability and implications of the use of potential sources of energy; and developing new energy sources.
- Comprehending the dynamics and trends of population growth and developing alternate means of control.
- Understanding diseases for the purposes of preventing them and developing improved methods of treatment and more effective and efficient delivery of health services.
- Investigating natural and synthetic foods and materials, their development and use, their disposal or recycling, their efficient use or substitution, and their interaction with human lifestyles and their change.
- Improving the understanding of interpersonal, institutional, and social problems, and developing and gauging the success of alternate approaches for alleviating them.

Adequacy of Present Knowledge

Scientific knowledge at present is sufficient to sustain major research and development efforts in all the directions just cited. Present understanding is adequate to help identify some of the major dimensions of the problems discussed in the report, to give general guidance for formulating plans of applied research and development to attack them, and to offer some potential—although often limited—options for responding to the challenges.

But significant advances in knowledge are needed in order to understand these and other problems more thoroughly, and to develop alternate strategies and technologies of assured effectiveness. Major advances in virtually all the basic and applied sciences are required for this purpose, as indicated in earlier chapters of this report.

In addition, knowledge from the diverse scientific disciplines and applied sciences needs to be synthesized and focused on the complex of problems discussed earlier. Such integration could sharpen the understanding of the interactions among the problems, help to identify knowledge gaps and priorities for filling them, and suggest directions for attacking the problems which would neither aggravate related problems nor create serious new ones.

The Nation's Research Effort

The important role of science and technology in meeting the many challenges prompts the question: Is the Nation's effort in research commensurate with the magnitude and nature of the challenges?

The current research effort, we believe, is inadequate to prepare the Nation for the challenges which are now emerging and which are likely to face it in the future. This conclusion is based upon consideration of these challenges in relationship to recent trends in the level and direction of basic and applied research, as shown by the following indicators.

1. National expenditures (Federal and private) for basic research rose by 13 percent in current dollars over the 1970-74 period, but declined by 10 percent in constant dollars.[1] Over the same period, outlays for basic research by the Federal Government (the prime source of such funds) increased by 6 percent in current dollars, but decreased by 15 percent in constant dollars.[2]

2. National expenditures (Federal and private) for applied research increased in current dollars by 21 percent between 1970-74, but declined in constant dollars by 3 percent. Federal expenditures during this period rose by 15 percent in current dollars, but fell by 8 percent in constant dollars.[2]

3. Obligations by the Federal Government for basic research in areas other than defense and space—such as health,

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[1] Constant dollars, by accounting for the effects of inflation, reflect the actual level of research activity more accurately than current dollars.

[2] *National Patterns of R&D Resources,* National Science Foundation, U.S. Government Printing Office, Washington, D.C., 1975 (in press).

environment, and natural resources—grew by 36 percent in current dollars (11 percent in constant dollars) between fiscal years 1970-74. Obligations for applied research in these "civilian" areas increased by 64 percent in current dollars (34 percent in constant dollars) over the period, while outlays for development rose by 72 percent in current dollars (40 percent in constant dollars).[3]

4. Federal obligations for basic research in the defense and space areas increased by 3 percent and 14 percent, respectively, in current dollars between fiscal years 1970-74, while declining by 14 percent and 7 percent, respectively, in constant dollars. Outlays for applied research in defense-related areas rose by 16 percent in current dollars over the period, but declined by 5 percent in constant dollars. Obligations for applied research in the space area decreased by 40 percent in current dollars and 51 percent in constant dollars.[3] [4]

5. Federal obligations for "untargeted" basic research—research that is not linked with a specific problem area—grew by 20 percent in current dollars between fiscal years 1970-74, while declining by 2 percent in constant dollars. Obligations in this area, which are aimed at strengthening the general base of scientific knowledge, dropped from 13 percent to 10 percent of total Federal obligations for civilian R&D.[3]

These data indicate the complexity of recent shifts in the level and direction of the Nation's research effort. Certain trends, however, emerge clearly.

- The level of basic research activity in the Nation declined significantly between 1970-74, as measured in constant dollars.
- National expenditures for applied research decreased also, but to a lesser extent than for basic research.
- Federal obligations for both basic and applied research expanded in civilian areas as a whole, increasing at an annual rate of about 3 percent in constant dollars between 1970-74.

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[3] Special analysis prepared from *An Analysis of Federal R&D Funding by Function*, National Science Foundation, NSF 74-313, U.S. Government Printing Office, Washington, D.C., 1974.

[4] The general purpose research conducted as part of the overall R&D efforts in defense and space contributed in significant ways to scientific knowledge and technological capability relevant to "civilian" areas, as illustrated in earlier chapters of this report. To that extent, cutbacks in defense and space research represent a reduction in efforts applicable to some of the problems now facing the Nation.

- These increases in Federal obligations for research in civilian areas were concentrated in selected fields. The field of health accounted for 53 percent of the total growth between 1970-74, the environment for 25 percent, natural resources for 9 percent, and energy for 8 percent.

- Federal obligations for "untargeted" basic research declined slightly between 1970-74 in constant dollars, while decreasing substantially as a fraction of total Federal obligations for civilian R&D.

Earlier chapters indicate that present and developing problems of a civilian character require for their alleviation a broader base of knowledge than is now available; that much research is needed to fill this gap; and judging from past experience, that scientific knowledge and research capabilities will be needed tomorrow for problems that cannot be formulated clearly today.

V

RECOMMENDATIONS

Application of the Nation's Research Capability to Civilian Problems

The Nation's capabilities in science and technology should be brought more fully to bear on the full range of civilian problems of the kind discussed in this report: population, health, food, energy, minerals, weather and climate, and the environment.

These capabilities, in addition, should be directed to deepening and expanding general scientific knowledge through "untargeted" basic research, so that the Nation will be better prepared to meet the unforeseen challenges which assuredly will arise in the future.

We believe that the science and technology enterprise has the capability to increase its research efforts effectively in both directions. We believe, further, that the Nation's research effort, in both its basic and applied aspects, should be expanded. The extent of the expansion should be sufficient to reverse recent declines in the overall level of effort and provide for growth in the years ahead, so that the Nation can obtain the unique benefits available from a vigorous research endeavor.

The success of this effort requires the participation of the Nation's entire science and technology enterprise—the Federal Government, private industry, and the universities.

Role of the Federal Government

In the last few years the Federal Government has increased its expenditures for research in civilian areas such as health, energy, and the environment. This has been accomplished under the difficult condition of a declining total Federal budget for R&D, in terms of constant dollars.

Although the growth of civilian research funding has been substantial, further expansion of this component of the Federal budget appears to be needed—now and for some time into the future. This applies particularly to civilian problem areas for which existing market mechanisms and incentives for research do not exist or are too weak to elicit the necessary action from the private sector.

The Federal Government, in addition, should continue to assume major responsibility for support of "untargeted" basic research, because of the broad and multipurpose uses of the results, and because investment by the private sector is limited by the inability to capture the full returns from such research.

Role of Private Industry

Only a fraction of the increase in national research expenditures needs to come, or should come, from the Federal budget. Private industry should provide a significant part of the overall funding. Greater investment in research by the private sector could be fostered through government policies, regulations, and incentives that create a favorable climate for innovation and investment.

It is believed that the expanded effort by industry should emphasize the development of new and improved products and services and the enhancement of productivity. These actions, combined with enlarged production capacity in some industries, could help measurably in controlling inflation and strengthening the Nation's position in international trade.

Role of the University

The principal role for the universities is in the area of basic research. These institutions should continue to have prime responsibility for conducting basic research, by virtue of their unique capabilities and traditions in this area.

A part of the aggregate R&D activity of the Nation must be reserved for long-term basic research that is not tied specifically to present problems. Basic research, by expanding scientific knowledge, provides optional responses to unforeseen challenges that will arise in the future. Such research, in addition, supplies indispensable knowledge for intelligent and efficient planning and direction of the rest of the R&D effort. In this regard, the results from basic research constitute the infrastructure on which the whole system of innovation and rational management of technology is based.

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