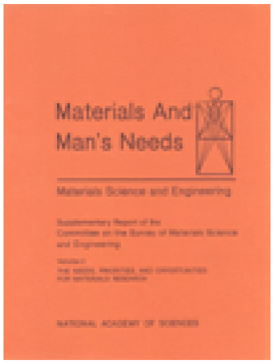
Materials And Man's Needs

Materials Science and Engineering

NATIONAL ACADEMY OF SCIENCES

Materials and Man's Needs: Materials Science and Engineering -- Volume II, The Needs, Priorities, and Opportunities for Materials Research

Supplementary Report of the Committee on the Survey of Materials Science and Engineering, National Academy of Sciences

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THE NATIONAL ACADEMIES
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MATERIALS AND MAN'S NEEDS

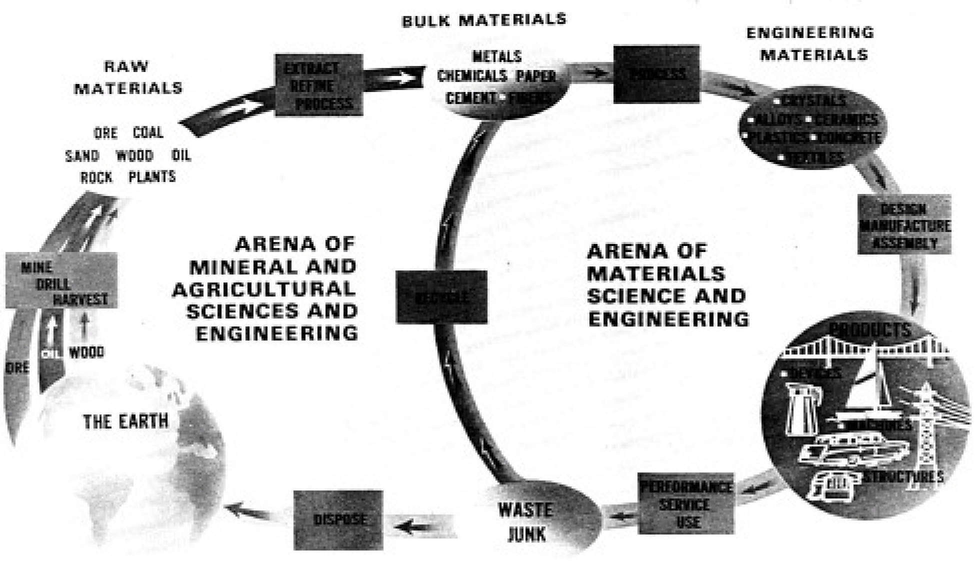
SUPPLEMENTARY REPORT OF THE COMMITTEE ON THE SURVEY OF MATERIALS SCIENCE AND ENGINEERING

VOLUME II

THE NEEDS, PRIORITIES, AND OPPORTUNITIES FOR MATERIALS RESEARCH

NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D.C. 1975

THE TOTAL MATERIALS CYCLE



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Supplementary Report of the Committee on the Survey of Materials Science and Engineering

VOLUME II

THE NEEDS, PRIORITIES, AND OPPORTUNITIES FOR MATERIALS RESEARCH

NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D.C. 1975

NOTICE

MATERIALS AND MAN'S NEEDS

SUPPLEMENTARY REPORT OF THE COMMITTEE ON THE SURVEY OF MATERIALS SCIENCE AND ENGINEERING (COSMAT)

The content of this Supplementary Report is part of the basis for the Summary Report of the NAS Committee on the Survey of Materials Science and Engineering. In contrast to the Summary Report, however, the views expressed here are those of the various contributors and do not necessarily represent a consensus of COSMAT.

Frontispiece: A schematic representation of the materials cycle, portraying its global nature and principal stages.

PREFACE

The Summary Report of the Committee on the Survey of Materials Science and Engineering (COSMAT) was published in the Spring of 1974. It was based on informational inputs generated by numerous committees, panels, and individuals. That background information has now been organized into this Supplementary Report, Volumes I to IV.

In assembling this extensive resource, a complete editorial function was not attempted. Thus, occasional redundancies and overlaps as well as some unevenness in style and coverage will be noted. There will also be found views, and perhaps contradictions, that did not make their way into the Summary Report, inasmuch as the latter reflects a consensus of COSMAT. Nevertheless, we believe that it will prove useful to the science and engineering communities, as well as to others concerned with the broader implications of technology, to have available the rich store of information that was collected by COSMAT.

We have organized the present Supplementary Report as follows:

Volume I—The History, Scope, and Nature of Materials Science and Engineering, containing Chapters 1, 2, and 3, is concerned mainly with tracing the history and evolution of materials technology, and of materials science and engineering in particular; also with describing the dimensions of the present role of materials in society; and with a study of the way in which materials science and engineering operates as a multidisciplinary field.

Volume II—The Needs, Priorities, and Opportunities for Materials Research begins, in Chapter 4, with a discussion of how materials research is related to various national goals or "areas of impact." In Chapter 5, the results of a comprehensive survey of materials research properties are presented, both for applied research related to these areas of impact and for basic research. Chapter 6 provides a description of several of the more prominent materials research opportunities, again both basic and applied.

Volume III—The Institutional Framework for Materials Science and Engineering (Chapter 7) describes the industrial, governmental, academic, and professional activities in materials science and engineering in the U.S. In the industrial section, emphasis is given to illustrative descriptions of materials technologies and to the roles of materials scientists and engineers in various types of industry. The governmental section describes the ways in which the federal government is involved with the performance and support of materials science and engineering. The academic section contains detailed qualitative and quantitative information on the status and trends in university education and research both in "materials-designated" and "materials-related" departments and in materials research centers. In the professional section, consideration is given to the characteristics and numbers of materials scientists and engineers, as well as to their professional activities and opportunities.

Volume IV—Materials Technology Abroad (Chapter 8) deals with many facets of materials technology, as practiced in other countries. In collecting this information, it was often difficult, or even impossible, to delineate policies and practices specific to the materials field from those pertinent to science and technology in general. In such cases, the broader situation has been reviewed on the assumption that its applicability to the materials sphere is implicit. Volume IV surveys national policies and administrative structures for science and technology, education, R & D, institutions, technology-enhancement programs, technical achievements, and international cooperation. Much of the content revolves around the general theme of technological innovation.

It is surely obvious from the magnitude of this Supplementary Report that COSMAT is enormously indebted to a wide diversity of committees and individual contributors, whose inputs and insights have proved so valuable. The COSMAT Panels, Committees, and Consultants are listed in the Summary Report. They and other individual contributors are also referred to in this Supplementary Report.

COSMAT is deeply grateful to Marguerite Meyer, Beverly Masaitis, and Judy Trimble for their indefatigable efforts in the typing and assembling of these four volumes; theirs was a prodigious task, indeed. We are also most indebted to Amahl Shakhashiri for her careful editing of these volumes.

And once again, COSMAT wishes to acknowledge the support of the National Science Foundation and the Advanced Research Projects Agency in this undertaking , carried out under the aegis of the Committee on Science and Public Policy of the National Academy of Sciences.

Morris Cohen, Chairman
William O.Baker, Vice Chairman
Committee on the Survey of Materials Science and Engineering
September 1975

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MATERIALS AND MAN'S NEEDS

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Chapter 2:	The Contemporary Materials Scene
Chapter 3:	Materials Science and Engineering as a Multidiscipline
Volume II	The Needs, Priorities, and Opportunities for Materials Research
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CHAPTER 4

NATIONAL OBJECTIVES AND THE ROLE OF MATERIALS SCIENCE AND ENGINEERING*

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*This chapter is based primarily on the work of Hans H.Landsberg and Roland W.Schmitt of COSMAT Panel VI and on inputs from several of their colleagues on COSMAT and at the General Electric Company.

CHAPTER 4

NATIONAL OBJECTIVES AND THE ROLE OF MATERIALS SCIENCE AND ENGINEERING

INTRODUCTION

The Nature of National Goals

There are different kinds of national goals. Some are ultimate objectives of society and are as old as the Constitution and its amendments. These goals define the kind of society we try to be, but they are not, as a rule, reducible to tasks for science and engineering. “Life, liberty, and the pursuit of happiness” are objectives that can be and are advanced by achievements in science and technology, but one would find it hard to derive from them specific programs in MSE. We may call them aspirations, principles, concepts, ideals, or goals, if we like.

Below this towering top comes a layer of other comprehensive national goals that embraces and defines areas of endeavor. Provision of free education for all is an old one; free medical care for the aged a more recent one While subject to change in detail, these are nonetheless continuing objectives, but, in any hierarchy of goals, they still lie above those that are more directly related to technological or materials tasks.

Moreover, one does well to think of a wide spectrum of kinds of goals as well as of a ranking. Various types of goals in the science and technology field alone are, for example—

Large, discrete tasks of social utility (e.g., model cities, urban mass-transportation systems)

Complex, open-ended programs (e.g., weather prediction, oceanographic program)

Large research tasks, with likely social utility (e.g., Apollo, Mohole)

Large fundamental research tasks of uncertain outcome but great social utility (e.g., nuclear fusion, nuclear propulsion)

Correction of social deficiencies (e.g., poverty, genetic defects)

Improvement of productive performance (e.g., reduction in mortality, increased man-hour productivity)

Specific inventions (e.g., aircraft-noise suppressor, alternative to internal combustion engine)

etc. etc.

Similar diversity exists along other classes of goals, i.e., one can distinguish between social goals, goals of scientific understanding, goals associated with pragmatic application of knowledge, and surely others.

Anyone searching for a repository of national goals or anything approaching it will be disappointed. Some goals are so persistent and fundamental that they are built into the conscience of the nation and of every citizen. The various "freedoms," both from and to, are of that kind. Others are implied in the structure of American society. Easing of upward social mobility, for example, would be hard to identify in any piece of legislation, yet it is undoubtedly a pervasive goal. So is increased man-hour productivity. These are canons by which we live and act.

As one leaves the loftier goals and focuses more on the recent past, it becomes easier to identify specifically formulated goals; this is largely because they cannot be taken for granted, are not "self-evident," but arise out of changing perceptions, as crystallization of widely-felt needs, as responses to events, or sometimes as "brainchildren" of illustrious citizens. In short, as the level of aggregation drops, the degree of specificity increases. As a result, one can ascertain and assert more forcefully that a goal does in fact exist, and one can more easily link the likelihood of its achievement to activities in MSE.

A useful distinction can be made between goals that have been formulated at some level of government—usually at the federal level—and are embedded in a piece of legislation, an Executive Order, a regulation, and those that rest on a less conspicuous basis, yet partake of the nature of national goals. The "conquest of polio" as compared with the "conquest of cancer" serves to illustrate the difference. The latter is an organized and specifically financed societal goal embedded in a federal statute. The fight against polio, supported financially largely by the annual "March of Dimes," undoubtedly was as much the expression of national desire, but its implementation was diffuse, unstructured, and left to individual initiative and excellence.

In the category of the less articulate, an interesting national goal and of significance to MSE is one that might be called "economic strength." While there exists a whole fabric or arsenal of laws designed to facilitate the smooth functioning of the economy (to strengthen competition, safeguard the sanctity of contracts, minimize labor disputes, encourage inventiveness, etc., etc.) one can point only to a single piece of legislation that sets up "economic strength or (disregarding recent misgivings as to its validity) "growth" as a national goal. That legislation was the Employment Act of 1946, which was aimed at establishing "maximum employment, production and purchasing power" as a national goal, or as a trinity of goals.

Only once in recent times has there been a governmental attempt to formulate specific national goals as guides to policy. That was under the Eisenhower Administration, when it adopted the recommendations of the Presidential Commission on National Goals. A different approach was taken by President Nixon when he set up in the Executive Office a "goals research staff" intended to be a permanent feature but disbanded after it had rendered its first report to the nation. The chapters of that report, issued July 4, 1970, are entitled “Population Growth and Distribution,” “Environment,” “Education,” “Basic National Science,” “Technology Assessment,” “Consumerism,” “Economic Choice and Balanced Growth,” and “Toward Balanced Growth.” Obviously, these are not goals. Rather, the topics suggest that in the process of selection, the Staff tried to determine in what areas conflicts would in the future have to be resolved, objectives established, and debates carried on.

Given the difficulty of defining goals and finding documentary support, the multiplicity of types of goals, their changing nature and stress, and COSMAT’s reluctance to consider itself appropriately composed for conducting an exercise in determining comprehensively what the nation’s goals seem to be, we have chosen a more modest way for evaluating the relationship between goals and MSE. We have selected some areas of national concern that affect all citizens in their daily lives and some that affect the nation’s fate as a whole, and have endeavored to show how needed advances can be assisted by contributions from MSE. We have concentrated on areas where (a) the materials aspect is, if not critical, at least obvious, (b) the contributions that materials advances might make are more easily demonstrated. Change is also a characteristic of the goals of interest to the materials community: change in the priorities among goals and changing emphasis within each. Changing priorities show up clearly when we consider either federal funding alone, overall public spending, or expenditures as reflected in the Gross National Product. Trends within broad goals are discussed extensively in the balance of this chapter.

Limiting our review of federal spending to the recent past, we can clearly identify a number of trends in the allocation of funds (see Table 4.1). Defense, space, and international affairs, in which grouping the first accounts for the lion’s share, declined from 62 percent in 1955 to 37 percent in 1972, though absolute amounts for the same period rose from 42 to 86 billion (current) dollars. The relative decline was due mainly to the continuing and rapid rise in outlays aggregated under the generic term “Income Maintenance;” this item rose from 15 to 85 billion dollars over the same 17-year period and is now about equal to the defense/space/international affairs group in magnitude. Income maintenance comprises above all social security, welfare, and veterans pay, but also includes access to medical care and education.

In relative terms, investment in human and physical resources has risen even more rapidly, as have housing and community development. There are important differences, however. For one thing, the absolute amounts involved are much smaller. Secondly, in the case of investment in physical resources (commerce, transportation, natural resources), growth has been discontinuous; a jump occurred in the second half of the 1950’s, and relative outlays have been on a plateau since. Thirdly, by way of contrast, in the case of housing and community development, the rise has been very recent. Only in the area of investment in human resources has there been a steady absolute as well as relative upward movement in federal spending, mostly in the field of education (Medicare outlays in this auditing scheme are carried under “income maintenance”).

Federal outlays, of course, constitute only a portion of public spending. State and local government expenditures account for the balance. These have

Table 4.1 Changes in Federal Budget Outlays,[a] 1950–1972, Selected Fiscal Years

Category	1955	1960	1965 (Percent)	1970	1972
Defense, space, international	61.7	53.6	49.6	44.3	36.6
Income maintenance	22.0	26.7	29.0	32.4	36.2
Investment in human resources[b]	2.2	2.5	3.2	5.8	6.2
Investment in physical resources[c]	2.3	6.4	7.8	5.7	6.4
Housing and community development	0.7	0.8	1.0	2.7	3.5
Net interest on debt	6.9	7.5	7.3	7.3	6.2
Other	4.1	2.5	2.1	1.8	5.0
	100	100	100	100	100

Source: Setting National Priorities—the 1972 Budget, Brookings Institution (1971) p. 13.

a Not adjusted for sales of assets

b Education, training, health

c Commerce, transportation, natural resources risen more rapidly than federal funds: from not quite 40 billion (current) dollars in 1955 to 132 in 1969 (the most recent year for which published data permit these comparisons to be made). Put differently, state and local expenditures have advanced from 36 to 43 percent of total governmental expenditures between 1955 and 1969, with schools, highways, and welfare accounting for the bulk of state and local outlays. If one then aggregates public expenditures at all levels of government, it turns out that in 1969, defense and international affairs for instance, accounted for 27 percent (as against the more than 40 percent in the federal picture), and education for over 16 percent (compared to about 6 percent under the total "investment in human resources" item in the allocation of federal funds). Going beyond public spending, Table 4.2 presents society's total expenditures in the 1960's, cast in terms of specified national goals as patterned by a continuing study of the National Planning Association. Significant features of the presentation are the slower than average rise of national defense, agriculture, international aid, housing, and R&D. On the uptrend side are social welfare, education, transportation, health, natural resources, and private plant and equipment. By and large then, the picture parallels the one portrayed by the changes in public spending, except that all spending for housing is down, while governmental spending is up.

The private consumption sector is of course a vast mix of incommensurables. To get closer to an understanding of its evolution in terms of materials, Table 4.3 presents a breakdown into three major categories.

Perhaps the most interesting feature of Table 4.3 is the relatively rapid rise in expenditures for durables as compared with nondurables and services, though the increase in the last-named category precisely equals that of the entire group (and of GNP as a whole). It suggests that the trend toward services is not nearly as pronounced in private consumer expenditures as in the economy as a whole. With regard to goods, it does indicate that there has been much growth in precisely that segment of private consumption where materials can have their greatest impact: durable goods.

A final comparison, before we draw some conclusions for the impact on the materials community of shifting public-expenditure trends, pertains to the relationship between the funding agency and the consumer of the result of funding. That is, in the case of defense and space outlays, the funder is at the same time the principal, if not the only, consumer of the product arising as the result of the funded expenditures. Such expenditures made, in other words, consitute close to 100 percent of the GNP for that function. In sharp contrast, federal transportation outlays represent only 6 to 7 percent of the output of the transportation industry, and still only 20 percent when state and local expenditures are included. In education and manpower, federal outlays represent a little over 10 percent of the GNP in that segment, but the percentage rises to nearly 90 when state and local expenditures are factored in. The corresponding figures in the health sector have recently run about 25 and 40 percent, respectively. They are lowest of all in housing; whether or not state and local expenditures are included, governmental outlays represent only about 6 percent of the output used.[1]

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[1] Data from Economic Report of the President, p. 101, 1970.

Table 4.2 Expenditures for National Goals, 1962 and 1969 (in billions of 1969 dollars)

Goal Area	Expenditures in		Percent Change,
1962	1969	1962 to 1969	
Private consumption	$418.5	$579.6	38.5%
Private plant and equipment	62.0	98.6	59.0
Urban development	84.0	94.7	11.0
Housing	37.5	35.4	–5.5
Other urban facilities	46.5	59.3	13.0
National defense	66.5	78.8	18.5
Social welfare	46.4	71.1	53.0
Health	43.5	63.8	46.5
Education	41.8	64.3	54.0
Transportation	39.3	61.5	56.5
Research & development	21.1	26.9	27.5
Natural resources	7.1	10.1	42.0
Agriculture	8.2	7.8	–5.0
Environmental quality	–	6.3	–
International aid	6.1	5.3	–13.0
Manpower training	0.1	2.0	–
GNP	678.0	931.4	37.5

Source: National Planning Association

Table 4.3 Expenditures for Private Consumption, 1962 to 1969 (in billions of 1969 dollars)

	Expenditures in		Percent Increase
Category	1962	1969	1962 to 1969
Durable goods	$52.0	$90.4	72.5
Nondurable goods	193.0	247.5	28.0
Services	174.5	242.0	38.5
All categories	418.5	579.6	38.5

Note: Details may not add to totals due to rounding
Source: National Planning Association

The above sketch suggests four major implications for the materials field. First, those segments of public spending that were prominent in funding R&D have suffered a relative decline. Second, the segment that has increased most in relative importance, i.e., income maintenance, has little direct linkage with materials. Third, those segments that have increased and do have an association with materials problems (housing, transport, etc.) account for only a minor share of the GNP generated in these sectors, i.e. whatever funding is performed will not, as compared with, say, defense, be directly translated into a ready market for the output. Fourth, the rising importance of state and local spending spells a shift to human resource development, prominently education (see above) and thus represents growth in an area in which so far at least materials have not played a key role.

Given the enormous weight of “consumer expenditures” in the nation’s GNP, it is obvious that such inarticulate goals as durability, reliability, performance, safety, low-cost repairability, etc. pose a continuing challenge for MSE. Yet the play of the market is the only mechanism for coupling goals and materials, and as we have pointed out above, it functions far less directly than in areas where the purchaser has a very direct role in the specifications (defense, space etc.). One reason is that often the consumer cannot really specify what he wants, and if he does, his desires may not find a producer responding.

In consumer areas, however, one must be careful not to confuse poor manufacturing practices with unsatisfactory material properties. Not know-what is achievable at reasonable cost, the consumer has a long list of desiderata but he cannot match it with potential solutions. All he can do is test different products offered and proceed by trial and error. Consumer choice is limited by the range of choice presented to him in the market place.

Another poorly articulated goal, moving ever more forcefully onto center stage is materials substitution. Nobody and everybody has responsibility for it. The manufacturer will act on the basis of cost differentials, evaluated in terms of the firm’s profits. The consumer will act in equally narrow terms that include cost and convenience. Society’s interest that ranges from favoring materials with a longer-run supply potential to materials having less noxious environmental impact is basically an orphan, or we should say, has been until recently. In the future, one may expect greater emphasis on substitutions. These substitutions will be (a) the direct substitution of one material for another (aluminum for copper, nickel for silver, polyurethane for cork, etc.); (b) development of new ways to perform the same function (transmitting a telephone signal through transparent fibers in conjunction with light-emitting semiconductor diodes at the transmitting and semiconductor photodetector diodes at the receiving end, or substitution of integrated circuits for transistors and vacuum tubes, or development of wholly new adhesives); and (c) development of substitute technologies that could radically alter the patterns of materials demand (nuclear vs. fossil-fuel power generation, communication through solid-state electronics vs. transportation of people and goods).

Constraints of various kinds will call for much more sophisticated approaches to substitution, and MSE is bound to play a major role in this sphere.

In the balance of this chapter, we attempt to (a) specify some goals in the fields of communication networks, space, electrical power, transportation, health services, the environment, and housing, and then document their evolution by way of governmental pronouncements and actions in various contexts, and (b) illustrate how the achievement of these goals is connected with specific developments in MSE.

The sectors chosen for reviewing the connection between materials research and national goals do not exhaust all segments of economic activity; nor do they cover the broader range that forms part of the materials research priority study described in the next chapter. Specifically, the subsequent discussion omits reference to what are broadly called consumer and producer durables. The reason is simply that one cannot identify anything there that could be regarded as a “national goal” beyond such very loose matters as “competitiveness,” “least-cost production,” etc. Nevertheless, these broad areas do present many important challenges to materials technology and some of these, in the area of defense, the supply of and demand for materials, and automation of industrial processes and methods, are briefly described. This chapter concludes with an overview of goal-oriented materials research opportunities and needs, many of which apply to several economic sectors.

The Relevance-Tree Approach

The approach to the identification of critical materials needs has generally been a “shredding out” of specific materials problems and tasks from the more broadly formulated goals; often referred to as the relevance-tree technique. For example, one may derive from the goal of abundant, reliable, low-cost, and environmentally acceptable electric power the route, among others, of controlled thermonuclear fusion and, by an extension of the process, the requirement of a material with specific tolerance for radiation damage.

According to Jantsch[2], technology transfer occurs vertically via at least eight levels. At each level, there can also be horizontal transfer. These are summarized in Tables 4.4 and 4.5 where some examples are also given. The eight levels represent progressively increasing (or decreasing) “levels of aggregation” —moving upwards in the tree involves embracing increasing breadth of techniques and technologies in order to achieve the desired social or economic objective.

Vertical transfer can be up or down. When upwards, the science and engineering can be regarded as creative in that it creates new technologies, new functions, and new opportunities for society. When downwards, the science and engineering can be regarded as responsive in that it is responding to perceived societal needs.

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[2] E.Jantsch, Technological Forecasting in Perspective, O.E.C.D., Paris, 1967.

Table 4.4 Illustrative Levels in a Relevance Tree (after Jantsch)

		Technology Transfer Level	Horizontal Transfer	Vertical Transfer
↑ Direction of Progress ↓	Impact Levels (Outside Materials Science and Engineering	8. Society	Ethical Constraints on Social Goals	Implications of Communications for Society
		7. Social Systems	Technical Air Program for Developing Countries	Defense and Other Natural Aspects of Commications
		6. Environments	Invasion of Other Industrial Sections	Communications Sector of Industry
		5. Applications	Demand for Auxiliary Support Systems	Market for Communications Systems
	Development Levels (Within Materials Science and Engineering)	4. Functional Technological Systems	Diffusion of Existent Technology	Solid-State Communication Systems and Functional Sub-Systems
		3. Elementary Technology	Merger of Discrete Technologies	Integrated-Circuit Technology, etc.
		2. Technological Resources	Fructification of other Fundamental Technological Research	Diffusion Techniques Planar Techniques, etc.
		1. Scientific Resources	Empirical Postulation of a Scientific Theory	Recognition of the Natural Phenomenon of Semiconduction: Majority and Minority Carrier Concept, etc.

Table 4.5 Example Programs Displayed According to Relevance Trees (after Jantsch)

	Example 1 (Exploratory, creative, creates opportunities)	Example 2 (Normative, responsive, responds to needs)
8.	World-wide instant communication, artificial organs for man, etc.	Space as an environment to benefit man, space as challenge, etc.
7.	Technological gap between countries, extension of defense and space strategies, support for development of artificial organs, etc.	National space program
6.	Changing relationship between systems and components manufacturer (growing together), diversification into medical electronics, city-building, hospital management, etc.	Planetary mission
5.	Applications to new tasks, incentive for mass production, market strategy, business cycles for rate of successive and related innovation	Nuclear rocket propulsion
4.	Low-cost high-reliability electronic systems increase in capacity for volume and mass unit, etc.	Nuclear-thermal propulsion unit, nuclear-electric (for example, ionic) propulsion system
3.	Integrated circuits, number of component functions accommodated, frequency, power dissipation, feasible reject level for mass production	NERVA-type or SNAP-type nuclear reactor technology, gaseous nuclear fuel technology, thermionic technology, metal vapor turbine cycles, etc.
2.	Level of microminiaturization feasible with current and future techniques, limits of molecular engineering, high-frequency potential, etc.	Three-fold specific impulse by use of hydrogen as propellant in connection with nuclear external heating, continuous low-thermal acceleration by electric propulsion, etc.
1.	Quantum electrodynamics, quasi-particles, etc.	Conditions for and energy yield of nuclear fission, thermodynamic superiority of low molecular-weight gases, ionization potentials, zero-gravity in orbit (for low-thrust spiralling out), thermionic principle, etc.

Example 3		Example 4	Example 5
8.	Abundant power	Eliminate poverty	Eliminate poverty
7.	Power Network system	Increase exports	Population control
6.	Thermonuclear power	High-technology, e.g. computers	Distribution of birth-control techniques to public
5.	Plasma containment	Large-scale memory	Birth-control techniques
4.	Large superconducting solenoid	Bubble-domain memory system	Pill
3.	Cryogenics	Integrated circuitry	Drug manufacture
2.	Superconducting alloy metallurgy	Garnet crystal growth	Biochemical synthesis
1.	Physics of superconductivity	Cooperative behavior of magnetic lattices	Biochemistry

Jantsch labels levels 1 through 4 in Tables 4.4 and 4.5 as Development Levels, being mainly technical in nature and resulting at the 4–5 boundary in a functional technological system. Levels 5 to 8 are labelled Impact Levels, being mainly segments of society which are affected by the results of the science and engineering. MSE is clearly most immediately associated with levels 1 through 4. In its creative mode, the output of MSE is a new functional technological system. In its responsive mode, society has perceived a need for a functional technological system which MSE should help produce.

The relevance tree should also be interpreted on a suitable time scale. It takes time for progress upwards through the various levels to occur. Basic research on materials, for example, might not begin feeding information upward for 10 years or more.

As the specifics of the generally formulated or implied goals are modified, so the MSE tasks will vary. In the case of health, there seems to have taken place a shift from conquest of specific diseases or disturbances to delivery of care for large numbers. In the case of energy, we see emphasis on such items as the breeder reactor and on conversion of coal to gas or liquid form. Once these are commercially feasible, emphasis may change again, this time perhaps to such long-run concerns as minimizing the ejection of heat into the atmosphere and, therefore, to the potential of solar energy. Yet, the national goal of abundant, low-cost, reliable, and environmentally sound energy is unlikely to change. Thus, what follows deals generally with goals that may be assumed to be prominent for some time but the specifics of which are subject to modification.

TELECOMMUNICATION NETWORKS

The Nature of Telecommunications

In the broad sense, telecommunications (TC's) are all-pervasive. TC's transmit information in the form of electrical signals from one place to another. The information may be speech, or numerical data, or radar signals, or television pictures, or facsimiles, or signals from sensors such as seismographs, electrocardiographs, heat, pressure- and light-sensitive devices.

TC's impinge on virtually every aspect of life—on work, on pleasure, on health, on business and commerce, on transport, on family. Materials can be ordered by telephone, medical doctors consulted, and business carried on in a very different way from that which preceded the large use of telephony. International communications have shrunk distances, brought families closer together, allowed television viewing of events as they occur the other side of the world. The impact of television has been profound on the economy, the dissemination of news, and the social patterns of life. Similarly, the impact of computers and their interconnection through telephone and data networks is immense—an example from common experience is the vast improvement in air-travel reservation procedures and in seat assignments occasioned by the use of computers coupled to a nation-wide, and in some cases, international communications network.

TC's are the nervous system of a nation. They are vital for its everyday activity, as has been recognized by Japan which has afforded them top priority in its development plans for the 1970's. TC's, along with computers, have had an impact on man's information-handling tasks and capacities which compares with the impact that the steam engine and other motive powers had on man's physical tasks and capacities.

The opening paragraph of the final report of the President's Task Force on Communications Policy (Rostow Report, August 14, 1967) aptly states this theme: "Few technological changes have had so profound an effect on the human condition as the development of telecommunications. Man today lives in a maze of electronic signals; it is certain that their influence on the quality of his environment will be even more important in the future than is the case today."

The same report goes on to state: "The essential goal of national policy, in our view, is an optimal rate of improvement in our telecommunications capability, based on progress in science, technology, and the arts of management, and addressed to the growing needs of its users." This is a rather vague definition as definitions of national goals go, but it is indicative of a growing awareness in the late 1960's that the nation should develop a coherent policy for the telecommunications field.

One of the reasons why national goals for telecommunications have seemed less urgent than they might have been lies with the structure of the nation's telecommunications network and the way it is managed. The U.S. is the only country in which the operation of the telecommunications network is not the direct responsibility of the government. Instead, it has been left to private enterprise to develop in response to customers' needs, although under the close and continuous monitoring and regulation provided by the Federal Communications Commission (FCC) and various other state and local utility commissions. In many ways it can be said that the U.S. has found an ingenious compromise between the extremes of outright nationalized industry and private monopoly. The FCC is the instrument designated by Congress to exercise regulatory powers over communications carriers. As such it is the prime agency for formulating and implementing policy for TC.

The major portion of the nation's TC network is operated by the Bell System which has, as its corporate policy, enunciated by A.T. and T. President W.S.Gifford in 1929, "the best possible telephone service at the lowest cost consistent with financial safety." In view of the position of the Bell System, it might not be inappropriate for us to regard this objective as in lieu of a national policy statement concerning the TC network.

In recent years, however, the FCC has followed a course designed to temper the dominant position in TC held by the Bell System. Though the TC network is often described as a "natural monopoly," the FCC is seeking ways to open it up to a greater number of private companies to share in providing the increasing scope and diversity of communications equipment and sources. The resulting arguments over whether the public interest is really best served by a fragmented network and industry or a unified one are outside the scope of this present study.

The issue of the Bell System is, however, an especially poignant one for the modern field of MSE. It can be fairly stated that the field got a big impetus with the discovery of the transistor at Bell Telephone Laboratories in 1947. In retrospect, it can be seen that the solid-state electronics industry which followed is what is responsible for the great diversity of communications equipment and the highly increased competition the Bell System now faces.

Dimensions of the Telecommunications Sector

TC systems are made up of three principal classes of equipment: terminal (both for sending and receiving), switching, and transmission. Some of the more common types of equipment that are used in these systems are listed in Table 4.6.

There are over 120 million telephones in the US today, close to two million non-broadcast stations authorized, and over 25,000 broadcast services. A recent study[3] projected the number of telephones for 1985 as 220 million, plus 3 million picturephones (about two-thirds of which will be used mostly for data or information services), and about 8 million data terminals connected to public and other networks.

TC's are a major factor in the national economy. According to Clay T. Whitehead, Director, Office of Telecommunications Policy,[4] during the past 20 years the communications industries' contribution to the national economy increased by over 500%, a growth rate almost double that of the economy as a whole and substantially in excess of the rates of such important segments as transportation and trade. The Bell System alone has been responsible for a major share of the nation's business expenditures for new plant and equipment, 10 billion dollars in 1970 (about 12% of the nation's total) compared with approximately 6 billion dollars for transportation and 2 billion dollars for mining, and it employs about 1,000,000 people.

In addition to these indirect effects of communications on the economy, the direct impact is substantial by virtue of the size of the industry. The Bell System alone, for example, accounts for 15% of the domestic copper consumption and is the largest single consumer of polyethylene.

Dependence of TC's on Hardware and Materials

TC's have become one of the most sophisticated forms of high technology, although a person using a telephone may be less conscious of the hardward than when he uses a car or an aeroplane. But advances in TC technology more often than not result from, or depend strongly upon, advances in materials technology. Some examples will help illustrate the point:

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[3] Paul Baran and Andrew J.Lipinski, The Future of the Telephone Industry, 1970–1985, Institute for the Future, Menlo Park, Calif., Report R-20, September 1971.

[4] Statement before the Subcommittee on Treasury, Post Office, and General Government, The Honorable Joseph M.Montoya, Chairman, Appropriations Committee, United States Senate, May 19, 1971.

Table 4.6 Types of Equipment in Telecommunications Systems

Terminal Equipment (Sending and Receiving)	
Telephones	Computers
Television cameras	Medical sensors
Television receiver	Industrial sensors
Alphanumeric displays	
Switching Equipment	
Relays	Electronic switches
Ferreeds	Memory devices
Transmission Equipment	
Wire	Coaxial cable
Radio and antennas	Microwave waveguide
Microwave and antennas	Satellites
Undersea cable	

The first successful transatlantic telegraph cable (1866) rested on the solution of the hitherto unknown problems of making, laying, and splicing cables that would be sufficiently robust and durable in the ocean environment.

Transcontinental telephone service opened (1915) only after ways had been found to build repeater amplifiers in order that intelligible voice communication could be carried this great distance. These, in turn, required the development of both high current-density oxide cathodes to replace the inadequate metal filaments of early vacuum tubes and a new magnetic material, permalloy, for the loading and inductance coils.

Radio relay systems in telephone networks made their appearance after World War II. The successful design of special high frequency tubes essential for this system was only made possible through the development of improved ceramic insulators (steatite) which had low loss at high frequencies and high temperatures—a development which required special attention to material purity and reproducibility of processing cycles to achieve the necessary control of microstructures.

But it was the discovery of the transistor at Bell Labs in 1947 that really opened the era in which materials technology became inextricably interwoven with advances in TC technology. Practical tansistors called for hitherto unheard of achievements in material (germanium and silicon) purity and perfection—landmark feats were the invention of zone refining and techniques for crystal growing. Since then, a steady stream of advances in solid-state electronic-materials technology (controlled alloying, diffusion, epitaxial growth, oxide masking, thermocompression bonding, etc.) has kept expanding the capability and capacity of electronic components and TC’s. The center of the stage is held at present by the integrated circuit (IC), a supreme achievement of MSE in which physics, chemistry, and metallurgy have been combined with electronic design and engineering to produce, via a procedure which involves hundreds of carefully controlled materials-processing steps, a complex functional piece of material—a material which, when it is energized, performs desired electronic functions such as amplification, memory, logic, calculation, etc., with a long-term reliability that would be virtually impossible using earlier discrete component technologies.

But the IC is not-the end of the long series of innovations that can be traced to the transistor discovery. Semiconductor technology stirred intensive R&D in other areas of solid-state science, and in 1958 there occurred another discovery, or invention, that is likely to be of enormous importance to TC’s in the future, the laser. Because their operating frequencies (optical) are so much higher than radio and microwave frequencies, lasers offer the prospect of the vastly greater numbers of communication channels that may be needed in the future as demand for communications continues to increase. The laser has, in turn, stimulated materials research aimed at a whole new family of optical devices—oscillators, amplifiers, modulators, memories, holography, photochromicity, visual display devices, deflectors, etc. Optical transmission lines based on ultra-pure glass fibers and integrated optical circuits are currently receiving heavy emphasis in order to complete the arsenal of components for a complete optical TC technology to supplement existing microwave and older technologies where traffic demands are sufficiently great.

Another, rather different measure of the interplay between materials technology and TC's is provided by the familiar telephone handset itself. It utilizes 42 of the 92 elements provided by nature (See Table 4.7); it contains among other things, 35 types of metals and alloys, 14 types of plastic, 12 varieties of adhesives, and 20 different semiconductor devices.

The increasing demand for TC's can only be met by continuous heavy investment in R&D aimed at finding new and better devices, improved switching and transmission methods, and better materials. The communication system to support the high volume of communications projected earlier will undoubtedly be materials-based; whether the transmission is by wire, radio, coaxial cable, microwave relay or satellite, by waveguide operating at millimeter wave frequency or by glass fibers using laser sources and various optical circuit devices based upon new materials discoveries; whether the switching is by electromagnetic relays, ferreeds, vacuum tubes, transistors, or opto-electronic devices; or whether the information storage is by magnetized wires or tapes, ferrite cores, integrated circuits, holography or photochromicity. (It would be physically impossible to meet today's demands with yesterday's relays and wire-based technology—the materials and power requirements alone would be prohibitive.) Present TC technology, now based very much on microwave frequencies and solid-state devices such as integrated circuits, may well have to be extended to optical frequencies in order to keep up with future requirements.

A feature of telephone-network planning is the systems approach in which new techniques have to be added to, or adapted to, existing networks. It would be far too costly to rebuild the whole network each time a new TC technology comes along. This implies, in turn, that all the devices and components in the network must be operationally compatible with one another, and must be chosen so as to optimize the overall performance of the network.

Whatever the technology, because of the vast amount of capital equipment needed nationwide, durability of the hardware and the reliability of its performance must be of the very highest standards.

All the above factors combine to place real pressures on MSE. In the past, these pressures have been repeatedly met through developments in materials and device technology. Many of these achievements, some examples of which are given in Tables 4.8 and 4.9, have gone on to have very significant impact in areas outside TC's as well.

Government Involvement in Telecommunications

Playing such a vital role in the nation's economy and welfare, yet tending by its very nature to be a monopoly (as with utilities, one does not have a choice between two separate telephone systems), the communications field is closely regulated by the government, principally through the Federal Communications Commission.

Some major events in the evolution of the federal government's involvement with communications are as follows:

1910	Man-Elkins Act; jurisdiction of interstate and foreign telephone and telegraph service given to the Interstate Commerce Commission.

Table 4.7 Elements in the Telephone Handset

Name	How Used
Aluminum	metal alloy in dial mechanism, transmitter and receiver
Antimony	alloy in dial mechanism
Arsenic	alloy in dial mechanism
Beryllium	alloy in dial mechanism
Bismuth	alloy in dial mechanism
Boron	Touch-Tone dial mechanism
Cadmium	color in yellow plastic housing
Calcium	in lubricant for moving parts
Carbon	plastic housing, transmitter steel parts
Chlorine	wire insulation
Chromium	color in green plastic housing, metal plating, stainless steel piece parts
Cobalt	magnetic material in receiver
Copper	wires, plating, brass piece parts
Fluorine	plastic piece parts
Germanium	transistors in Touch-Tone dial mechanism
Gold	electrical contacts
Hydrogen	plastic housing, wire insulation
Indium	Touch-Tone dial mechanism
Iron	steel, magnetic materials
Krypton	ringer in Touch-Tone set
Lead	solder in connections
Lithium	in lubricant for moving parts
Magnesium	die castings in transmitter, ringer
Manganese	steel in piece parts
Mercury	color in red plastic housing
Molybdenum	magnet in receiver
Nickel	magnet in receiver, stainless steel parts
Nitrogen	hardened heat-treated piece parts
Oxygen	plastic housing, wire insulation

Name	How Used
Palladium	electrical contacts
Phosphorus	steel in piece parts
Platinum	electrical contacts
Silicon	Touch-Tone dial mechanism
Silver	plating
Sodium	in lubricant for moving parts
Sulfur	steel in piece parts
Tantalum	integrated circuit in Trimline set
Tin	solder in connections, plating
Titanium	color in white plastic housing
Tungsten	lights in Princess and key sets
Vanadium	receiver
Zinc	brass, die casting in transmitter, ringer

Table 4.8 Summary of Some Major Achievements in Telecommunications Technology and Related Materials Achievements

Year	TC Achievements	Related Materials Technology Achievements
1844	First domestic telegraph cable.	
1866	First successful transatlantic telegraph cable.	Fabrication, laying, splicing of durable underwater cable.
1877	First domestic telephone service.	
1915	First transcontinental telephone service.	Oxide cathodes for vacuum tube amplifiers. Permalloy (nickel-iron) for loading coils.
1927	Negative feedback amplifier enabled multiplexing.	Quartz crystal piezoelectric filters. Modulators made from copper oxide varistors.
1929	Coaxial cable carrier system for broadband transmission.	Eventually made efficient, in 1939, through first application of polyethylene as a dielectric with low loss at high frequencies.
1947	Transistory discovery, and beginning of solid-state electronics.	Semiconductor verification and crystal growth.
1948	Microwave radio relay system.	Low-loss ceramic (steatite) insulators. Ceramic ferrites for isolators, circulators.
1956	Transoceanic Telephone cable.	Copper-beryllium repeater housings. Ultra-long life dielectrics and insulators.
1958	Laser invented— offers prospect of increased bandwidth.	Growth of suitably-doped refractory oxide crystals —ruby, sapphire led to demonstration of laser in 1960.
1960	Electronic switching systems.	Initially based on vacuum tubes, subsequently on solid-state electronics and integrated circuits.
Early ‘60’s	Millimeter wave system.	Development of ultra-straight waveguide tubing and joining techniques.

Year	TC Achievements	Related Materials Technology Achievements
1962	Satellite communications (TELSTAR)	Development of highly-reliable and radiation insensitive solid-state components; solar cells, transistors, etc.
1964	PICTUREPHONE	Stimulated development of silicon target camera tube.

Table 4.9 Summary of Some Materials Innovations in TC Technology

Material or Process	Category	Applications in Telecommunications
Metals		
Molybdenum Permalloy	High permeability Magnetic alloy	Loading coils; high frequency transformers and inductance coils; telephone relays and coils
Remendur	Magnetic alloy	Fereed relays for electronic switching
Remalloy, Permendur	Magentic alloys	Telephone receive diaphragms
Vicalloy	Permanent magnet	Twistor memory devices
Cobalt samarium copper alloys	High strength permanent magnet	Travelling wave tubes
Alnico	Permanent magnet	Telephone ringers
Vibralloy	Constant modulus alloy	Frequency-sensitive switches
Textured copper alloys	Spring materials	Relay springs, electrical contacts
Pure nickel alloys	Vacuum tube filaments	Microwave triodes; submarine cable tubes
High conductivity aluminum alloy	Electrical conductor	Exchange area telephone cable
Tantalum, tantalum nitride	Thin film conductor	Thin film circuitry; integrated circuits; resistors, capacitors
Lead-antimony	Soft alloy	Cable sheath
Copper-beryllium	Sea-water resistant	Submarine cable repeater housings
ZAMAK alloys	Die-casting alloy	Precision switchgear and handset piece-parts
Laminated sheets of copper and copper-nickel	Composites	Laminated coins acceptable to coin telephones

Material or Process	Category	Applications in Telecommunications
Plastics, polymers		
High density polyethylene	Thermoplastic	Cable insulation; cable sheath
Long-life polyethylene	Thermoplastic	Durable cable sheath
Impregnated, stabilized paper	Paper	Pulp insulated cable; metallized paper capacitors
Continuously vulcanized rubber	Rubber	Rubber insulated cable
Ceramics and Glass		
Low-loss steatite	Ceramic insulator	Supports in high-power transmitter tubes
High alumina	Ceramic insulator	Insulating supports, integrated circuit substrates
Freeze-drying	Preparation of ceramics	Improved ceramic composition and structure
Garnets	Magnetic ceramics	Microwave, components, filters, isolators
Ferrites	Magnetic ceramics	Magnetic memories
Nickel-manganese-cobalt oxide	Thermistors	Thermal stability of circuits
Potassium-sodium-niobate	Piezoelectric ceramics	Piezoelectric transducers and delay lines
Lead-zirconate titanate	Piezoelectric ceramics	Microphone transducers
Ultra-pure glass	Optical glass	Optical waverguides

Material or Process	Category	Applications in Telecommunications
Crystals		
Synthetic quartz	Piezoelectric	Ultrasonic transducers, frequency standards and filters
Silicon	Semiconductor	Junction diodes, rectifiers, Schottky diodes, field effect transistors, solar cells, microwave diodes, transistors; integrated circuits; camera tube targets; charge-coupled shift register and image sensing devices
Lithium tantalate, lithium niobate, barium sodium niobate	Ferroelectrics	Ultrasonic transducers, frequency filters; electro-optic modulators; optical harmonic generators; parametric optical oscillators
Gallium phosphide	Semiconductor	Light emitting diodes for alpha-numeric displays
Gallium arsenide	Semiconductor	Varactor diodes
Mixed III–V compounds	Semiconductors	Continuous room-temperature injection laser
Copper oxide	Semiconductors	Rectifiers
Zone refining	Purification process	Semiconductor devices; integrated circuits
Diffusion	Doping process	Semiconductor devices; integrated circuits
Oxide masking	Control of doping process	Semiconductor devices; integrated circuits
Epitaxy	Thin film growth	Semiconductor and magnetic devices; integrated circuits
Thermo-compression bonding	Connection technique	Integrated circuits

Material or Process	Category	Applications in Telecommunications
Neodymium-doped yttrium aluminum garnet	Lasers	Optical transmission
Substituted rare earth garnets	Magnetic	Bubble domain devices
Czochralski growth	Crystal growing	Semiconductors, ferroelectrics, garnets
Hydrothermal growth	Crystal growing	Quartz, garnets

1912	Radio Act of 1912; protects certain radio frequencies for governmental use.
1922	Interstate Radio Advisory Committee (IRAC) formed by Secretary of Commerce; to allocate frequencies among various federal agencies that use radio communication.
1927	Establishment of Federal Radio Commission; to classify, license, and regulate nongovernment stations.
1934	The Communications Act of 1934; creation of the seven-man Federal Communications Commission, an independent agency with regulatory powers over communications carriers that the Mann-Elkins Act had vested in the Interstate Commerce Commission and licensing power over radio communications that the Federal Radio Commission had exercised.
1951	Creation by President Truman’s executive order of a Telecommunications Advisor to the President.
1956	FCC consent decree which allows the Bell System to retain its manufacturing subsidiary, Western Electric Co. but with the latter allowed to sell only to the Bell System. In addition, all extant patents in 1956 were made freely available to any applicant and all future patents were to be made available on request but at reasonable royalties.
1958	Advisory Committee on Telecommunications convened by the Director of the Office of Civil Defense Mobilization.
1959	Proposal to set up a five-member special Telecommunications Commission failed to obtain Congressional approval.
1960	Task force appointed by President-elect Kennedy recommended transfer of all OCDM telecommunications powers to a new Office for Coordination and Development of Communications Policy within the Executive Branch.
1960	FCC allocates frequencies in bands above 890 Mc/s. Customer ownership of private microwave. Previously limited to right-of-way companies (rail, pipeline, public safety) and governmental agencies in addition to communication carriers.
1961	Transportation and communications service established; responsible for procuring and promoting economical use of transportation motor equipment, public utilities and communications service in executive agencies.

1962	Communications Satellite Act establishes COMSAT, a private corporation to be owned 50% by overseas carriers and 50% by general public. Space and ground segments open to competitive bidding.
1965	FCC, regarding ownership of satellite communication ground stations, assigns 50% to COMSAT, 50% to overseas carriers, with COMSAT as manager.
1965	FCC in allowing 50%-80% reduction in Bell System rates compared with private microwave tariffs raises question of discriminatory practices.
1966	FCC rules satellites should supplement underseas cable facilities and question is raised of whether private entities can build and own specialized satellite systems within the continental U.S.
1966	FCC considers interdependence of computer and communications services and facilities, and whether remote data-processing is outside of regulatory control.
1967	FCC considers applications by Microwave Communications, Inc. for setting up new facilities in domestic public point-to-point microwave radio service. Consent eventually given. About 1700 station applications pending by mid-1972.
1968	“Carterphone decision” on interconnections in which FCC ruled that the Bell System must allow entry and allow customer ownershipe of data modems, private PBX systems, and private point-to-point microwave.
1970	National Academy of Sciences reports on study of problems of interconnections and suggests some possible solutions.

The above partial list of public indicators of shifting emphasis in the general TC sphere gives some hint of the current trends: (a) the increasing diversity and complexity of TC—voice and data communication; satellites versus terrestial and submarine facilities, and (b) the growing fragmentation of the TC business, with increasing numbers of companies offering to provide pieces of the action. It seems that when the increasing complexity of TC’s calls more than ever for a systems approach and the economies of scale to achieve maximum cost-effectiveness (optimum combination from the customer’s viewpoint of quality of service versus cost). It remains to be seen whether the TC sector can continue to be innovative and efficient under the increasing constraints.

Tomorrow's TC Technologies

The full impact of telephone networks and computers on our pattern of living is still to be felt. Shopping, automatic billing, credit transactions, up-to-date information on sports events or on business, the storage and editing of written texts, translation of letters from or to a foreign language, all can be done by TC's.

A recent study[5] projected the technical evolution of the telephone plant, with widespread installation of such advances as time-division switching, stored-program electronic control, and data-link type signalling channels. Some of the conclusions are given in the following paragraph and Table 4.10.

> "Microwave radio will continue to carry the majority of interexchange voice trunks, but the use of satellite circuits and high-capacity waveguide buried transmission systems will increase.
>
> A number of new telecommunications services are likely to be offered in the future, particularly to the home. Prime examples include: plays and movies from a video library, computer-aided school instruction, 'cashless society' financial transactions, and facilities allowing executives et al. to work at home rather than commute.
>
> Such new services are unlikely to generate sizable revenues before 1980, but revenues are expected to rise rapidly thereafter, reaching about $9.2 billion per year by 1985 and about $19.7 billion by 1989."

There is no sign of a slackening demand by society for increased TC capacity, versatility, and reliability. Technologically, these demands translate into needs for communication at higher than ever frequencies and for new hardward inherently more reliable than existing devices. And these demands must be met at prices consumers are willing to pay.

For the foreseeable future, hopes for satisfying these demands are pinned on the continuing development of integrated circuits (inherently far more reliable and versatile than older vacuum-tube technologies), and the development of drastically cheaper long-distance broad-band microwave (particularly beyond 15 GHz), including satellites and waveguides, and optical communication technologies. In parallel with these developments of broad-band transmission capabilities, new switching approaches will be evolved to take advantage of the memory and logic capabilities of integrated circuits, magnetic bubble, charge-coupled devices, and minicomputers to perform message switching with addressed blocks of digitized information. New customer services will call for developments of inexpensive, reliable, visual displays and data terminals (replacing the more cumbersom cathode-ray tube and teletypewriter, respectively). Visual displays capable of capturing and storing a full picture frame for later viewing will be needed as well as cheap means for recording

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[5] Paul Baran and Andrew J.Lipinski, The Future of the Telephone Industry, 1970–1985, Institute for the Future, Menlo Park, Calif., Report R-20, September 1971.

Table 4.10 Characteristics of New Nationwide Networks that May Have an Impact on the Public Network

			Median Size 5 Yrs. After Emergence (Thousands)				
Information Network		Median Date of Emergence	(% Probability)				
Terminals	Locations	10	50	90			
1.	Banking system for cashless society transactions	1980	20	10			x
2.	Stock certificate clearing	1978	5	2	x		
3.	Biomedical network	1980	10	5	x		
4.	Hotel/Motel Reservations	1975	20	10	x		
5.	Police/Crime Prevention	1975	10	5	x		
6.	Education	1976	50	5		x	
7.	Post Office	1985	40	10	x		
8.	Credit Card Verification	1967	80	20			x

whole video programs. Mobile telephone service is also expected to grow.

These demands for new and improved TC technologies all translate into demands for new and improved solid-state devices and materials. Integrated circuit technology has to be developed further, particularly by reductions in dimensions and by better material composition and microstructural control. Failure mechanisms in all manner of devices under environmental-use conditions have to be elucidated and dealt with. A whole optical communication technology has yet to be developed—the present battery of lasers, modulators, detectors, and so on, impressive as they are individually, have not yet been worked up into an efficient, functioning communication system. Transmission media, particularly optical fibers, have yet to be proven in the field. New terminal-equipment devices, particularly solid-state display devices, are needed. These may be based on liquid crystals, on electroluminescent diodes for alpha-numerics, on bubble domain or charge-coupled devices. Similarly, solid-state cameras are needed—the charge-coupled devices look particularly intriguing for this. To meet all these demands for new devices, new materials will often have to be discovered or developed but perhaps the main emphasis in materials technology will be on processing—improving the ability to control composition and structure, and thereby to build in reliability.

It is hard to visualize the impact that future TC technologies will have on society and the way of life. But imagine what the way of life would be today without the telephone, if every message and discussion now carried on by telephone had to be conducted by mail service. In the future, videotransmission and picturephone terminals, for example, may have a similarly profound effect on society. Communication may become, increasingly, an alternative to travel. Many may even stay at home and communicate to work. The corresponding relevance of materials R&D is illustrated in Figure 4.1.

SPACE AND DEFENSE

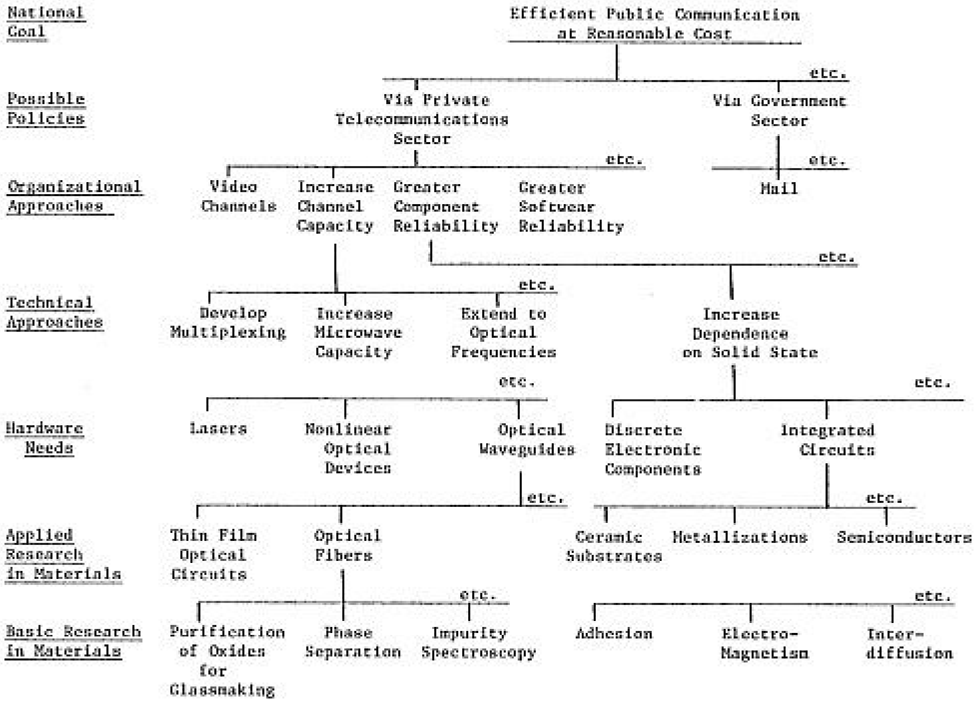
U.S. Space Program

“Now is the time to take longer strides—time for a great new American enterprise—time for this Nation to take a clearly leading role in space achievement which in many ways may hold the key to our future on earth.”

John F.Kennedy
State of the Union Address
May, 1961

The space effort of the U.S. had a modest beginning with the work of Robert H.Goddard (1882–1945) who carried on aerospace research involving rockets and balloons prior to World War II. Following the war, the U.S. obtained additional rocket and missile guidance expertise when the German

Figure 4.1 Partial Relevance Tree for Telecommunications



rocket pioneer, Wernher Von Braun, and his associates were moved by the army to Redstone Arsenal at Huntsville, Alabama where they continued their pioneering aerospace research and development activities. The Soviet Union's success in orbiting the world's first satellite in 1957 triggered a surge of public interest and competitive spirit in the aerospace field. This public interest resulted in a series of aerospace projects including Vanguard, Pioneer, and Explorer which were motivated partly by a national desire to demonstrate that this country could match Soviet exploits. Continued public interest in the "race-for-space" with the Soviets was elevated by President Kennedy in 1961 to a national goal of sending men to the moon and return, within the following ten years.

In July of 1958, the National Aeronautics and Space Administration (NASA) was created to conduct this country's peaceful aeronautics and space programs in accordance with broad national goals laid down by the U.S. Congress. The original Space Act stated, "The Congress hereby declares that it is the policy of the United States that activities in space should be devoted to peaceful purposes for the benefit of all mankind." These activities include such goals as: "The expansion of human knowledge"; "long-range studies of the potential benefits to be gained and the problems involved in the utilization of aeronautical and space activities for peaceful and scientific purposes"; and "the most effective utilization of the scientific and engineering resources of the United States."[6]

During the 1960's there was assembled, under the leadership of NASA, a very large mission-oriented scientific and technological team, perhaps the largest ever put together: at its peak in 1966, over 400,000 persons were engaged in the space program in government, universities, and industry. They made rapid progress in science and engineering; they devised management systems to handle extremely complex and interrelated problems and programs; and they forced development of newer and faster computers to aid them in their work. This effort required the development of systems which represented a new level of reliability and which worked effectively under severe or difficult operational conditions. Behind these new system developments were many technological advances in the form of (a) new materials with a level and uniformity of properties previously considered impractical to achieve, and (b) new processes and fabrication techniques which worked faster, more reliably, and with greater precision. In fact, the lunar landing timetable necessitated compressing into one decade technological advances that might normally have taken several.

During the 1960's, the public enthusiastically supported the lunar landing goal; but with the objective achieved in 1969, public backing for continued scientific missions to the moon began to wane, perhaps largely because other national issues such as the Viet Nam war, inflation, quality of life and environment, health, education, and urbanization claimed the increased attention of the nation.

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[6] The National Aeronautics and Space Act of July 29, 1958; Public Law 85–568, 85th Congress.

Funding of space activities has been greatly reduced since its peak in 1966, as is indicated in Table 4.11, from a high of 4.4 percent of the total federal budget outlays in FY 1966 to about 1.4 percent in FY 1972. This drop has been due to general budgetary considerations as well as to the fact that there does not now exist a widely-supported national goal in the aerospace field that compares with the well-defined, single objective of the Apollo manned space-flight program.

Projected space programs of the U.S. will be more limited in scope and in cost than Apollo. The preeminence of the Apollo program in the 1960's and the trend to near-earth programs in the 1970's is indicated in Figure 4.2. Specifically, major emphasis will be on manned earth-orbital flights, space science and applications R&D activities. The manned space-flight missions will emphasize both the Skylab and Space Shuttle.

The major focus of the orbital-workshop Skylab program will be on (a) studies of the sun, (b) space applications which include surveying earth resources and environmental interactions, (c) the use of the space environment for special processes, and (d) the effects of long-duration space flight on man. The Space Shuttle is regarded as a key element for future space operations in earth orbit. The earth-to-orbit shuttle provides a reusable vehicle for placement, retrieval, and servicing of satellites; short-duration manned and unmanned missions; and delivery of propulsive stages and payloads for high-energy missions. It provides savings in the cost of payloads because of the ability to repair and reuse payloads and because of the relaxation of the stringent weight, size and reliability requirements currently imposed on payload designers.

The space-science programs reflect emphasis on exploration of the earth's environment, the solar systems, and the universe through manned spacecraft and related ground-based observations. Typical of the explorer spacecraft in this mission ar the Orbiting Solar Observatory and the High Energy Astronomical Observatory. The latter spacecraft is designed to identify and observe gamma, cosmic and x-ray sources. Both programs involve international cooperation.

Planetary exploration is also emphasized in the space-science programs. Included are (a) the Mariner missions to Venus and Mercury, (b) the Pioneer missions to explore beyond the orbit of Mars, through the asteroid belt and into the vicinity of Jupiter, and (c) the Viking Mars orbiter and lander. Planning is also underway for Mariner-class spacecraft missions to Jupiter and Saturn.

Applications programs will emphasize the continued expansion of the use of near-earth satellites for meteorology, communications, navigation, geodesy, and earth-resources surveys.

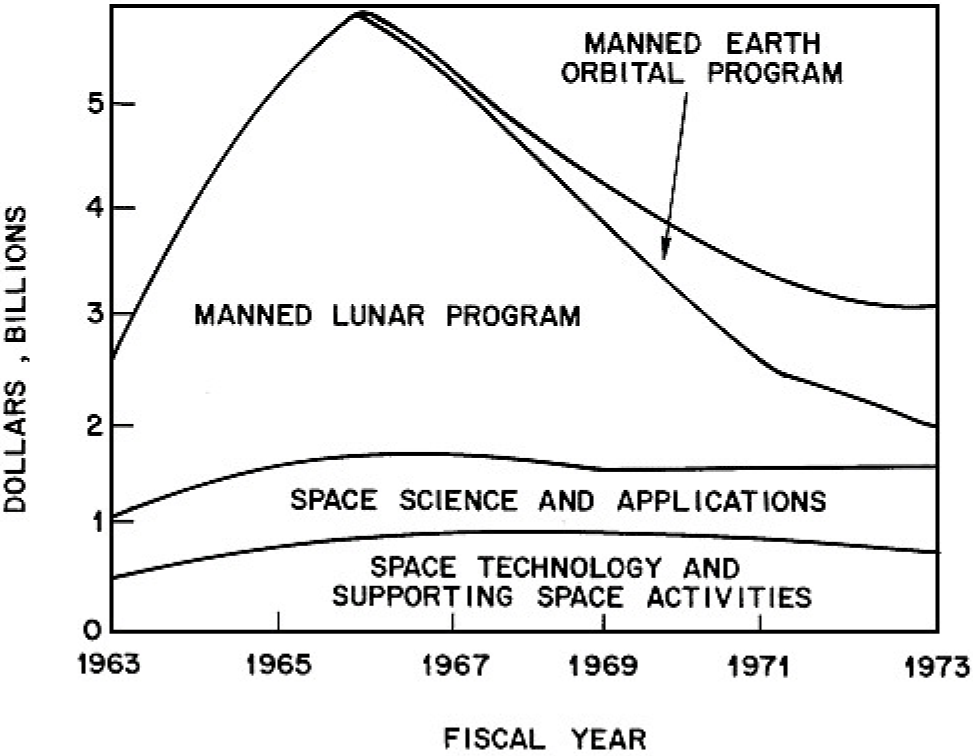
A major demonstration of the beneficial uses of space could revive public support for the space program. In particular, the new technology being developed in this program can potentially provide real and lasting solutions to some of man's social problems. Specific examples include radioactive waste disposal and low-cost electric power through solar-energy conversion.

Table 4.11 Space Research and Technology

Fiscal Year	Space Research and Technology Outlays (in millions)	Percent of Total Federal Budget Outlays
1973 Estimate	$3,191	1.3
1972 Estimate	3,180	1.3
1971	3,381	1.6
1970	3,749	1.9
1969	4,237	2.3
1968	4,721	2.6
1967	5,423	3.4
1966	5,933	4.4
1965	5,091	4.3
1964	4,170	3.5
1963	2,552	2.3
1962	1,257	1.2
1961	744	0.8

Source: Economic Report of the President, January 1972 Table B-64.

FIG. 4.2—EXPENDITURES FOR SPACE RESEARCH AND TECHNOLOGY



(FROM MARKET TOPICS — JAN. 28, 1972)

Materials Development and Space Achievements

In general, the achievements in space have not depended upon the use of exotic new materials. Instead, a highly developed and sophisticated systems-engineering approach has been employed in which materials and process capabilities have been pushed to their limits. There are several reasons for this. First, space flights are expensive and require a high degree of reliability for even minimum cost-effectiveness. Thus, it has been necessary and prudent to use materials which were thoroughly tested and characterized. Also, the regard for safety in manned space flights has dictated the need for redundancy wherever possible together with liberal margins-of-safety in design. Specifically then, emphasis has been on materials engineering of a high degree of sophistication rather than on new materials synthesis.

On the other hand, new adaptations of materials already developed exemplify innovative thinking as much as do new syntheses. As an example, the early use of heavy copper heat sinks for re-entry nose cones was a logical and predictable choice at the time, but the succeeding generation of re-entry thermal-protection materials (phenolic-nylon and phenolic-glass) represented a completely different approach. Few individuals involved in polymer development in the early days of the space program would have predicted that these materials with their relatively limited temperature capabilities could be used to protect man and equipment from the severe heat and structural loading environments of entry from outer space.

Similarly, materials such as thermal-control coatings, lubricants, optical materials, adhesives, seals, organic and inorganic structural materials and solar-cell covers have been developed, modified, and/or tailored for the space program. It is interesting that some of these materials were exposed to more severe environments during prelaunch testing than during actual flight. Also, many of the early fears which plagued designers did not materialize. For example, cold-welding in space did not occur nearly as frequently as was expected simply because the tenacious surface gas and oxide films carried along from earth were extremely difficult to remove. That is, exposure of a material to a vacuum environment of less than 10^{-10} torr does not mean that its surfaces are automatically cleaned.

Evidence that advances in materials, as well as in vehicle design, have been made at a steady pace through the years is attested to by the longer operating lives of spacecraft. Rittenhouse[7] made an analysis, covering the launch period from January 1958 to January 1967, of the length of time that some (81) of the U.S. unclassified scientific, weather, and navigational spacecraft have transmitted useful data. Their lives were plotted against the Year of the Space Age, arbitrarily assuming that 1958 was Year 1. It was found that the 90 percent confidence estimate for the lifetime of spacecraft increased from about 1/2 year in 1960 (Year 3) to 2 years in 1966 (Year 9). Extrapolation of Rittenhouse's data would indicate a 90 percent confidence lifetime of more than 3 years by 1975 (Year 18).

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[7] J.B.Rittenhouse, "Materials for Spacecraft Systems," AIChE Materials Conference, Philadelphia, Pennsylvania, March 31—April 4, 1968.

Many of the products, materials, and new fabrication techniques developed for the space program are currently being adopted as new or improved products or processes for home and industry. It is difficult, however, to determine quantitatively the extent to which space-inspired technology is responsible for such developments. This situation results from the fact that the reduction of technological advances to civilian practice is time-consuming and the aerospace industry is only one of a number of sources of new technological knowledge.

The general conclusions to be drawn from a review of the space-technology-stimulated developments involving materials and processes are: (a) the NASA contributions are many, both direct and indirect, and varied; (b) the major effect of the NASA contribution has been to cause the technological advancement to occur at an earlier date than it would have otherwise; and (c) the NASA contributions took place at all levels of technology, including step-changes, incremental advances, and consolidations. From these conclusions, it is apparent that one of the space program’s roles in advancing materials and processes technology has been to create a demand for the technology to fill. By creating this demand and, in some instances, by carrying out the appropriate development efforts, NASA further advanced the technology in the field, resulting in new products and processes.

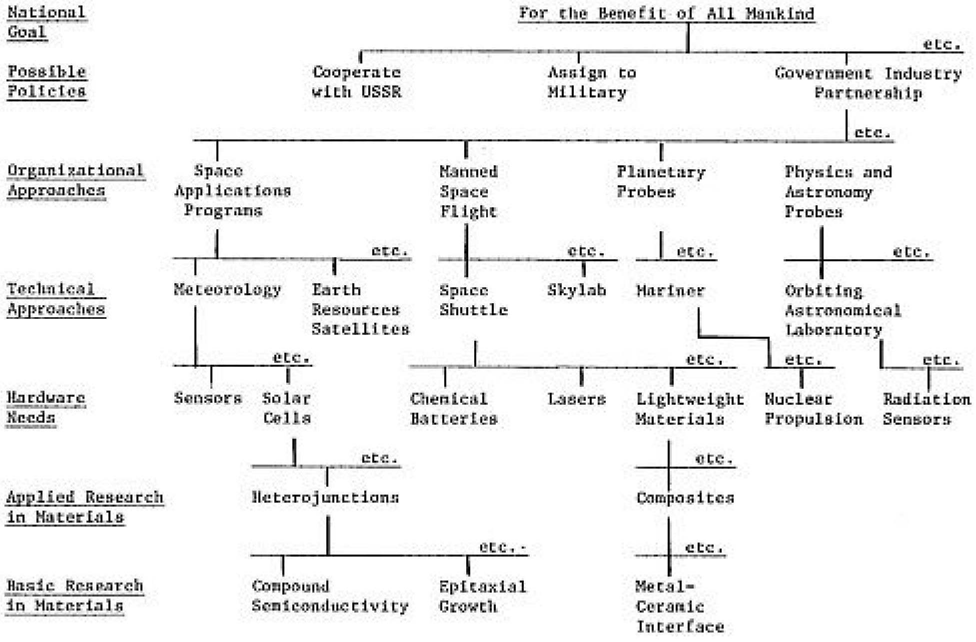
Material Needs of the Space Program

The on-going space program of the U.S. involves three general areas, namely, manned space flight, space science and space applications. Figure 4.3 is a partial relevance tree which helps show the connections between materials and process developments and the goals of this overall space effort.

Some requirements in common with the above three space areas indicate the need for: (a) ongoing research in the laser field if the potential of lasers is to be realized for space communications, power transmission, conversion, and propulsion; (b) materials for use in improved sensing devices and instrumentation for all aspects of the space program [High reliability sensors for earth-orbital spacecraft in particular offer the advantages of (i) rapidity and continuity of observation, (ii) greater freedom from weather disturbances, (iii) large-area views for regional synthesis, (iv) reduced data-acquisition times, (v) reduced costs, and (vi) higher quality data.]; and, (c) materials with long-life and extreme service capability for advanced batteries and power-generation systems, including thermionic, nuclear, isotope, and MHD.

The space-shuttle payload capability, and hence the payload cost, is very sensitive to the weights of the orbiter and booster thermal-protection systems (TPS) and structures. High insulative efficiency, rigidized ceramic-fiber insulations protected with a ceramic coating are currently the leading candidates for the TPS because of their (a) simplicity, (b) low density, (c) capability for repeatedly surviving the maximum expected surface temperatures, and (d) reserve margin. However, other materials such as superalloys, coated refractory metals, ablators, and carbon-carbon materials are being carried as backup materials in case unexpected difficulties should develop with the leading candidates.

Figure 4.3 Partial Relevance Tree for Achieving Sapce Goals



Advanced composites also offer the potential for significant weight reduction in the structure of the shuttle vehicles. To achieve the required level of confidence for their use, technological advances are needed in the design of structures to fully exploit their unique properties and in the development of methods for accelerated and proof-testing under simulated heating conditions, chemical environments, and foreign object damage.

A different kind of opportunity for materials research, development and fabrication lies not in the need for, and stimulation of, new or improved materials for the spacecraft, but in the use of the space environment itself for processing the materials, namely, under high-vacuum and low-gravity conditions. Recent analysis[8] suggests that technical benefits may result from preparing some materials and products in space. The two classes of materials which appear closest to satisfying the technical and economic constraints at this time are:

<u>Electronic Crystals</u>
Float-Zone-Refined Semiconductors
Solution-Grown Crystals
<u>Biologicals</u>
Vaccines for Human Usage
Cells for Human Usage
Viral Insecticides and Pesticides

It has been estimated that 30 to 50 space shuttle payloads might be generated from these product areas by the year 2000 AD. The total value of the payload could range as high as $1.5 billion.

Some Observations Regarding Materials in Space Technology

A major role of the space program in materials R&D has been one of stimulation. The program creates a need which is filled directly by industry or with the direct or indirect support of NASA. In general, most of these developments have been only modifications or extensions of existing technology, and the need simply stimulated or expedited the development of the material, process, or product. However, the developments and innovations have been unique because of the high level and uniformity of properties achieved as well as their characteristic high degree of reliability and reproducibility.

The space efforts of the U.S. will continue to emphasize reliability and long life, and improvement in performance capability. Specific short-range needs can be identified such as the development and application of thermal-protection systems and structures in the shuttle spacecraft. Longer-range requirements include the need for a wide range of new sensor materials,

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[8] L.R.McCreight and R.N.Griffin, “Manufacturing in Space-Payloads for the Space Shuttle,” Space Division, General Electric Company.

materials for laser-power transmission and communication and for space-power systems.

A unique feature of the continuing space program is the potential for new and improved materials through processing under space conditions (vacuum and low-gravity forces). In fact, space processing and the space-shuttle mission may have a symbiotic relationship. That is, low cost per pound of payload capability is mandatory for the exploitation of space processing, and space processing has the potential for being the major space activity which can utilize the large number of flights required to maintain low payload costs.

Note on Materials Science and Engineering in National Defense

The role of MSE in support of military institutions has changed less over the past two decades than has the concept of the use of military force. In general, materials are the underpinning of all military hardware. Their performance has much to do with the effectiveness, cost, and durability of weapons, communications, vehicles, and logistic support. To the extent that military force itself has social utility, the scientific and technological development of properties and processing methods for materials is of definite national importance.

In World War I, technology was on the side of the blockaded Central Powers, but their resources were ultimately overtaxed, while the Allies had access by sea to the world's minerals and agriculture. Superior German skills in synthetic nitrates, chemicals, and metallurgy prolonged the War but could not decide it.

In World War II, the scope of conflict was greater, and Germany was better prepared for a protracted struggle. Conversely, the Allied Powers found their trade lanes more disrupted by submarine warfare, and their domestic economies constricted by the logistic requirements of global war. Materials supply became a major problem. Technology was called on not only for materials useful in new kinds of weaponry but also to develop substitute materials to supplement stocks of short commodities. After that War, during the period 1945–1950, a major U.S. program was the building of a national stockpile of strategic and critical materials. The goals of this program were determined largely by the experiences with specific shortages in World War II. The assumption was made that the pattern of general war followed in 1914–1918 and 1939–1945 would continue, despite the emergence of nuclear weapons in the closing days of the second great conflict.

After 1950, the military requirements for materials presented no serious problems in supply. However, two new sets of materials problems did arise: (a) development of an array of materials with special properties to meet the extreme requirements of the new “strategic weaponry” in the nuclear missile age; and (b) development of flexible patterns of rugged and durable weaponry useful under conditions of informal wars.

Between 1950 and 1970, the major emphasis of military R&D in hardware was in the first category. A long list of abortive development projects were undertaken: Navaho, aircraft nuclear propulsion (ANP), the B-38, Skybolt, Dynasoar, nuclear powered rocketry, mobile nuclear reactors, the B-70 chemical bomber, and many other lesser projects. Nevertheless, some solid successes were achieved, notably with Polaris, Minuteman, and the Nike series.

Research and development of new materials and new processes accompanied both successful and unsuccessful projects, as well as in unrelated materials R&D to advance the state of the art generally. The federal investment in the high-technology materials and processes associated with advanced military systems has, indeed, produced a tremendous increase in these specialized knowledges and skills. Their use in commercial or other civil products tends to be limited by cost, by their high specialization, by security classification, and by the variety of obstacles to technology transfer. (It appears to be easier for this transfer to take place internationally than nationally; thus, while large sums were invested in the development of a U.S. titanium industry, the Japanese now surpass the U.S. in the production of quality titanium.) Nevertheless, many advances in MSE sought for military purposes have found use in commercial products: refractory metals, concentrated foods, arctic clothing, Pyroceram, high-temperature plastics, high-strength fibers for composites, and jet fuel are examples.

Experience since 1950 has tended to confirm the incorrectness of the assumption that future wars would be general and unlimited, following the pattern of World War II. Only with the greatest reluctance would one nuclear power challenge another to such mortal combat. The capability to inflict destruction has become intolerably great and the capacity to defend against it has diminished to the point of futility. The increase by orders of magnitude of nuclear weapons was accomplished by the development of nuclear fusion. The delivery systems became longer in range, faster in reentry, more accurate in guidance, and much more difficult to defend against.

Faced with the alternative of compelling all nations large and small to develop their own nuclear arms, the U.S. and the U.S.S.R. tacitly agreed to forego the use of these weapons to enforce their respective diplomatic postures.

Meanwhile, under the “nuclear umbrella,” a variety of smaller wars and informal guerrilla actions occurred. The U.S. became involved in a number of these and a highly interested observer of others.

The unsatisfactory and inconclusive nature of both the Korean War and the Vietnamese conflict, and the generally adverse political reaction to U.S. participation in these hostilities, suggest that conflicts of these types, like general war, have become high-risk enterprises with little advantage. The question is accordingly raised as to precisely what the future role will be of the institution of war, and of the U.S. military establishment. Only the future can disclose whether rejection of limited war will eventually force events toward general war, or whether some more acceptable alternative than war itself can be developed to serve the function historically provided by war.

The role of national military force has undergone more changes during the middle years of the 20th century than in all previous history. A virtual breakdown has occurred in the social institution of war. In the Napoleonic Wars and through the American Civil War, manpower mobilization was the crucial factor. By World War I, the mobilization of industry joined manpower as crucial. World War II saw weapons science and technology emerge as more than co-equal with manpower and industry. But the mobilization of science and technology for military purposes turned out to be irreversible. From 1950 on, the purposes and limitations of war itself were increasingly shaped by technology.

The social function of war is to assign a cost to intransigence—to the refusal to seek and find accommodation of international disputes through diplomacy. From this function, the role of diplomacy historically related to military force; the greater the force behind the diplomat the harder the bargain he could drive. The relation of military force to diplomacy has today become decidedly equivocal.

In addition, the manifestation of military force was historically necessary to establish its credibility. By “showing the flag” and by military demonstrations of force and readiness to apply it, nations contributed to the bargaining power of their diplomats. The manifestations also took the form of military presence in unstable areas, in small occupations, and in arms races of various kinds—as in the design of a military rifle, the tonnage of naval vessels, the “weight of metal” such vessels could discharge, or numbers of combat aircraft deployed or deployable.

Since 1950, the advent of nuclear-tipped intercontinental ballistic missiles has reduced the concept of arms races to an absurdity. The ability to destroy an adversary has advanced so much faster than has the ability to defend national territory that the national goal stated in the Preamble to the U.S. Constitution—to “preserve the common defense” —seems totally out of reach.

Establishment of the nuclear umbrella—the deterrent force—may eliminate the prospect of general war by making the cost of intransigence prohibitive. Distaste for the partial, inconclusive, protracted, and costly nature of limited wars renders our democratic society in the U.S. unready to respond to less than total challenges in the future.

As long as the nuclear umbrella remains credible and as long as potential rivals of the U.S. are willing to forego covert incursions into the U.S. sphere of concern, this status quo may remain acceptable. But what happens if other nations seek to take advantage of the U.S. preference for this peaceful status quo? At what point will the climate of public opinion change? What military actions will future U.S. leaders find necessary? What military equipment will be appropriate for such a response? And what materials will be needed for such equipment?

In devising a materials science and engineering strategy for military requirements of the future, a number of constraints apply. For example:

- There is the prospect of progressively more limited military budgets;
- There is the prospect of limited willingness of military leaders to divert dollars from manpower to hardware, and from hardware to the development of technology of utility;
- There is the indeterminacy as to the hardware requirements of the future for military purposes;
- There is the long time span for development of new materials extending from their first production in the laboratory to their actual use in military design; there is often a poor coupling of research to development; of R&D to design, and of advanced design to standardization and quality control;
- There is the diffused nature of personnel engaged in MSE, and the

tendency of dollars for their support to fluctuate from year to year;

- And finally, there is the necessity for military projects and systems to achieve a higher ratio of successes to failures, bearing in mind that materials performance is a foremost limitation, and that materials need to be ready when a military design concept is ready for decision.

In summary, military materials science and engineering needs to do a better job with less resources, to plan more carefully, to identify future needs, and to work patiently and systematically to meet them; it has to improve the assurance of reliable performance; to related more closely to design engineers, and generally to develop a posture of flexibility to meet many kinds of unforeseen problems quickly and competently with little hope of reward or even official support.

Then what are the options? It would seem necessary to raise the technological level in non-military areas of technology. For more than two decades, the U.S.S.R. has been doing this, as for example by designing agricultural trucks and heavy harvesting equipment along military lines. It would seem necessary to use greater selectivity in undertaking development projects, not being content with doing things because they can be done, but rather choosing among alternatives on the basis of carefully thought-out criteria of probable usefulness. It would seem necessary to steer a careful course between a low-risk, low-payoff strategy of incremental improvement and a high-risk, high-payoff strategy of major advance. A similar trade-off is necessary in the institutions of MSE: between the large, bureaucratized institution with high overhead, loose supervision, and low rate of productivity and creativity, and the contrasting small facility with a “subcritical mass” level of effort. Another trade-off must be found between stop-and-go programs, with shifting goals, fluctuating support, and high turnover, as against persistent plodding on unrewarding tasks. It is necessary to develop ways of economizing on the “second half syndrome” —the well-known phenomenon that 90 percent of the research is accomplished in the first half of the project time.

How many elaborate programs of materials R&D are addressed to improving the performance of materials used in items of military hardware that are soon to be phased out? If we recognize that the time required to perfect a new material in the laboratory is indeterminate but considerable, and winning acceptance for it thereafter can require a decade or two, are we in effect flogging dead horses? In the design of military programs of materials R&D, the time-phasing of military hardware systems is a key factor, and in the time-phasing of military hardware the future military posture and international relations of the U.S. are key factors.

There is no question about the ability of American scientists and technologists to come up with improvements in the materials used in military hardware. But the future prospect is one of curtailed budgets for military R&D. The design of the entire MSE program of the Department of Defense should reflect this reality. Establishment of R&D priorities is necessary. In addition, some kinds of research are clearly appropriate for both military and civilian uses. If budget emphasis is to shift to the latter, it is only reasonable to shift the supproting R&D as well. Then, too, if materials R&D is to be a shared enterprise, care should be taken to provide an effective arrangement by which to communicate and share the results of the shared R&D.

Over the past decade, an outstanding job has been done by the Office of the Director of Defense Research and Engineering in coordinating the design of programs of the military departments in materials science and engineering. Tasks have been systematically identified in relation to present and prospective military hardware in support of present missions. An evolution of the McNamara era in the Department was the concept that tasks should be budgeted by mission. As originally conceived, this concept called for the development on paper of alternative hardware concepts, and choices would then be made among these, mission by mission. However, by now the hardware decisions and missions seem to have stabilized and materials tasks are rather reliably identifiable. It is less clear, however, that the kinds of hardware related to military missions are as stable as this sequence implies, for the future. To translate a strategic concept of the Joint Chiefs of Staff into weaponry requirements is almost an impossible task because the concept is itself inaccessible to those who need to make the inferences about weaponry. The translation of weaponry requirements into feasible design concepts again takes years. And only then can design engineers begin to think in terms of materials of construction.

Today, because of the severe political penalties of design failure and cost overruns, the pressure on design engineers is heavy to minimize engineering risk. Materials are selected on the basis of reliability, in preference to their potential for advanced performance. Thus, even if military materials research programs are successful in relating their efforts to current hardware, the prospect is slim that new candidate materials will win consideration in time to be put into service.

There is no reason to suppose that the fall-out from civilian MSE will be of less value to the military services than has been the fall-out from military MSE for civilian uses. Glass-plastic composites may have been developed originally for refrigerators, but were found to be good applications in nose cones, while Pyroceram was developed originally for nose cones and was found excellent for coffee pots. The ultimate goal in military materials R&D is to have in being a wide array of well-characterized materials with established production methods and fabricated by established processes, and providing a full assortment of properties under a wide range of environments at a reasonable dollar cost. It is expected that vigorous civilian-oriented R&D will contribute significantly to this goal. One remembers that the first alloy used in jet engine turbine buckets in the U.S. was Vita-lium, a dental alloy.

In summary, the goals of military MSE require a closer surveillance of what is taking place in non-military MSE together with exchange of technical information from military sources to civilian users and from civilian sources to military users. A strengthened program of non-military MSE supported by the federal government, while not directly applicable to current military hardware, has a high probability of contributing to meet military requirements in the long-range future. It will also serve to strengthen the national economy, from which the resources are drawn to support the military posture. Strengthened management of scientific and technical information in a two-way flow can maximize the efficiency of the interdependency between military and non-military MSE, and this flow too will strengthen the flexibility of the military posture while strengthening the civilian economy.

NATIONAL GOALS IN ELECTRIC POWER

Public Policy and National Goals

If one were to formulate a contemporary national goal in the electric power field, one would have to say that it is the “abundant, low-cost, reliable supply of power under conditions compatible with environmental quality standards.” Looking critically at each of the adjectives, we would conclude that “abundant” means meeting demand at prevailing rates; “low-cost” means not subject to disproportionate price increases from traditional levels; “reliable” means subject to interruptions only in major emergencies beyond the supplier’s control; and the reference to “environmental compatibility” means complying with environmental controls and policies as spelled out at different governmental levels.

While not overly specific, such a goal represents a far more precise formulation than has prevailed in the past. Indeed, in the first thirty years or so of the electrical industry’s existence as a commercially viable segment of the U.S. economy, public policy in its regard was largely a by-product of policy directed toward navigable waters and especially the right to build dams. Even the Federal Water Power Act of 1920 (often incorrectly cited as the Federal Power Act) that set up the Federal Power Commission and gave it authority to license hydroelectric plants built on streams subject to federal jurisdiction was more concerned with comprehensive river development than with electric power as such; in fact the Commission was made up of the Secretaries of War, Interior, and Agriculture. A full-time commissioner system was not legislated until 1930 and regulation of interstate transmission and sale at wholesale not until 1935 (the latter remaining practically dormant until the early 1960’s). The intent of this type of legislation was to have natural monopolies become regulated monopolies, protect the consumer on a broader scale than local or statewide, and to protect the investor from losses through the operation of holding companies.

Stricter regulation coincided with an increased federal role in ownership. Again, though, the implicit goals were as much regional development and reduction of unemployment as provision of electricity. The Great Depression gave birth to TVA and to the rural electrification program, and established the federal government as an important supplier. At the same time, the idea of strengthening rate regulation by using costs of power emanating from publicly-owned facilities as a “yardstick” took hold. While often criticized in both concept and execution, the “yardstick” theory has persisted.

To summarize, the events of the 1930’s, traceable in several legislative actions, established a multiple role for the federal government: as a regulator of investor-owned suppliers; as a lender of low-interest capital; as builder and owner of large systems, first hydroelectric then steam; as a

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[Footnote: The Department of Defense and the various Armed Services have reviewed and developed detailed lists of materials R&D problems pertinent to their missions. Since these reports are generally available we do not explore these materials R&D problems in this report.]

marketer of wholesale power; and as owner and operator of transmission facilities.

The banner under which these developments took place carried changing inscriptions, as we have shown—protection of navigable rivers, consumer protection, investor protection, regional development, economic growth generally, aid to rural areas, and so on. To these was added in the early 1950's the exploitation of newly discovered nuclear-fission technology for peaceful purposes, giving the federal government yet an added and highly important role: that of promoting the development, supplying, at least initially, the fuel for, and generally watching over, the application of a highly complex new power-generating source.

Yet, despite the growing public role in electricity supply, one is hard put to find any formulation of a national goal until perhaps the 1964 National Power Survey which focussed on "abundant, low-cost, reliable power supply" and the obstacles to its achievement, high among which was better coordination among the different parts of the industry, each born of and subject to a specific legislative design and propelled by a different philosophy.

Ironically, when the ink was hardly dry on the 1964 Survey, a new and powerful element had begun to make its mark on the electric power industry, e.g., effects of generation, transmission, and consumption on the environment, embracing fuel extraction and transportation, generation, both conventional and nuclear, site location, effects of water and air emissions at higher than ambient temperatures on water and air, etc., etc. Thus the barely established goal of "abundant, reliable, and low-cost" power supply was amended to include "environmentally compatible," an addition that found legislative expression in the National Environmental Policy Act of 1969 and the various amendments to the Water Quality and Clean Air Acts, some passed since, some now pending, and others still to come, including siting and probably more general land-use legislation.

Thus, for the electric power industry, the 1970's are likely to become as fateful a decade as were the 1930's. But in contrast to the multiplicity of motivations and objectives in the thirties, few if any directly aimed at power supply, in the public policy of the seventies one may for the first time discern a clearly articulated objective—made up, to be sure, of several strands requiring reconciliation and trade-offs among themselves but nonetheless recognizable as a national goal. That electric power had come of age in this sense was demonstrated in June 1971, when the President sent an unprecedented "Energy Message" to Congress. While defining goals more generally, as discussed above, the Message also pointed to more immediate objectives; of special interest to the electric power industry were the development of a demonstration breeder reactor, commercially viable coal gasification, and economic sulphur removal from stack gases.

Mention must be made also of the role of the judiciary in defining the scope of newly formulated goals, especially in matters of environmental compatibility. While still in flux and as yet without Supreme Court pronouncements, it is clear that the coursts have been inclined to interpret legislation with heavy stress on environmental protection.

The Structure of the Industry

As shown above, the electric power industry in the U.S. is an amalgam of public and private interests. It is also an industry in which there has developed an unusual degree of partnership between equipment suppliers, equipment users, and government, in moving into new areas of opportunity.

While the manufacturers of equipment are organized as normal profit-making companies operating freely in the market, the utilities are regulated monopolies, with territorially-limited franchises that require them to supply power relatively uninterruptedly in their franchised areas, at rates set by State and Federal Power Commissions as a result of hearings.

About three-fourths of electric power generated in the U.S. emanates from public utilities that are investor owned. Federal facilities contribute not quite 15 percent, state and municipal sources about 10 percent, and rural cooperatives the small balance. While investor-owned utilities thus predominate in the aggregate, it is worth noting that a federal facility—TVA— is the country’s largest utility, in terms of generating capacity, and has moved from exclusive reliance on hydropower to coal-fired steam plants and more recently to nuclear reactors.

Antagonism between the public and private segments is substantially more muted than it used to be, as they have come to share many of the problems that afflict the industry as a whole (TVA’s use of strip-mined coal and of river flow for cooling water draws as much fire from opponents as does discharge of condenser water into a river or lake or selection of a new site by Consolidated or Commonwealth Edison). In any event, the two groups cooperate in R&D, via the Electric Research Council, which in 1972 sponsored about 70 projects costing $13 million annually.

The growth of the electric industry has been rapid and unceasing, so much so that the historical annual rate of 7 percent has come to be regarded by many as something akin to a natural law. And indeed, as on examines the order books of the industry, one comes away impressed by the volume and value of new capacity waiting to be installed. In 1971, electric utilities spent nearly $15 billion for new plant and equipment, obtained from an industry that embraces hundred of suppliers but in which concentration runs high both in share of transactions and in dominating the development of design and new materials. The utility branch is furthermore important as representing one of the principal clients of the long-term capital market. It is thus pertinent to inquire into the ways in which the industry is likely to achieve the multiheaded national objective in power supply in the context of a newly critical, vocal, and effective public opinion.

Industry Changes and Legislation

Five significant changes appear to be in store for the electric power industry, all connected in some way with legislation and each having some bearing on the materials community (See Table 4.12). These lie in the fields of environmental compatibility; availability and cost of fuels; capital structure of the industry; R&D activities; and lastly, the role of overseas procurement.

Table 4.12 Some Major Pieces of Legislation Relating to Electric Power

Date	Acts	Theme
1920	Federal Water Power Act (Federal Power Act after 1935)	Sets up Commission to license hydroplants
1935	Public Utility Holding Company Act	Establishes regulation of interstate electricity sales and transmission, and of companies engaged therein
1954	Atomic Energy Act	Permits construction and operation of nuclear plants
1964	Pacific Northwest Power	Regional power planning
1964	Private Ownership of Special Nuclear Materials Act	Reactor operation by utilities
1970	National Environmental Policy Act of 1969 (NEPA)	Imposes obligation to file overall environmental impact statements
1970	Water Quality Improvement Act	Regulates power plant discharges into water
1970	Amendments to Clean Air Act	Regulates power plant discharges into air

Examples of Proposed Legislation

Bill No.	Act	Theme
HR11896	Water Pollution Bill	Eliminate all pollutant discharges by 1985
HR11066	Power Plant Siting Bill	Public notice for power plants
S632,5992	Land Use Planning	Planning before power plant construction

Selected Court Cases

Decision Date	Case	Impact
1970	U.S. vs. Florida Power & Light	Suit against discharge of heated water into Biscayne Bay
1971	Calvert Cliffs	AEC responsible for overall environmental impact of licensed plants, under NEPA
1971	Quad Cities	AEC enjoined from giving partial operating license at reduced power

A. Environmental problems are now a major concern of the electric utilities and their suppliers. They run the gamut from damage to plants, structures, to people from stack gases in fossil-fuel-burning plants, to landscape defacement in hydroplants and transmission lines, to adverse effects on aquatic ecology by condenser water discharges, and to hazards from nuclear fission. They have attracted most attention in the matter of plant siting, and in turn this has been most pronounced with regard to nuclear power plants, as might be expected given the newness of the experimental installations to plants of 1,000 MW capacity and more, and the consequent lack of operating experience.

The stringent regulation and a proliferation of public-interest suits has resulted, since early 1971, in a practical freeze of licensing of new nuclear facilities and operating restrictions on some of those already licensed. The apparent shift of concern over hazards from control of routine operations to accident prevention and thermal effects on water has not removed obstacles to licensing. If anything, it seems to have hardened the look now being taken at the depth of fundamental knowledge concerning behavior of parts and materials even in inprobable malfunction contingencies. Moreover, stringent court interpretations of AEC's responsibilities under the National Environmental Policy Act of 1969 have launched the Commission, the utilities, and their consultants into searching inquiries concerning the implications of nuclear power for all conceivable impacts on the environment. Consideration is being given to "power parks" and remote locations, including offshore siting; undergrounding of distribution lines has been making rapid headway, and 15–20% of new transmission lines are also expected to be underground by the close of the decade.

More extreme measures such as proposed but defeated in "Proposition A" of the 1972 California State Primary, which would have banned construction of nuclear power plants in the next five years, may be expected to gain attention as society grapples with the problem of reconciling competing objectives. The potential contribution of MSE is discussed below.

B. Cost and availability of fuels have become matters of extreme concern. At the same time, various legislative restrictions are in the offing. California's "Proposition 9" would have outlawed offshore oil drilling; state and now federal legislation has been aimed at restricting strip mining for coal (in the context of more radical proposals to ban it altogether); the effect of the Mine Safety Act of 1969 is expected to further increase the cost of coal; and emphasis on low sulphur content has restricted the sources of coal and raised its cost. A national concern over the long-term availability and cost of uranium fuel has given impetus to a government/utility commitment to build and operate a demonstration breeder reactor. A site has been agreed upon, funds have been pledged, and proposals from reactor builders are being evaluated in 1972.

C. The above-cited cost increases will be compounded by rising cost of construction, loss of revenue, and the added financing costs due to construction and licensing delays; higher capital costs of nuclear plants compared to fossil plants also aggravate the industry's problem of attracting adequate capital. If for no other reason, reduced generating plant costs and higher plant efficiencies will be increasingly sought in the 1970's, and materials advances play an important part in both of these.

D. The electric utilities have recently come under increasing criticism for not undertaking adequate research and development. Estimates put 1971 R&D funding by utilities at about $60 million per year, or 0.25% of revenues; but in June 1971, the Electric Research Council produced a report projecting considerable increases in R&D expenditures by the "industry" (doubling over a 5-year period) defined, however, as consisting of the utilities, the electrical equipment manufacturers, and the govenrment. Increased R&D on materials is indicated, but no specific dollar amounts are proposed. As of the Fall of 1972, utilities had pledged substantial amounts to a joint R&D program, greatly exceeding those spent in past years. (Pledges in the Fall of 1972 approach $40 million for a 1973 program, and are expected to reach $75 million.)

A different approach has been proposed in the so-called "Magnusson Amendment" —an amendment suggested by Senator Magnusson to S. 1684 which calls for the imposition of a 0.15 mil per KWH tax on electric utility bills to finance R&D. It is thought that such legislation could lead to the creation of some type of "National Power Laboratory" and there is some indication that the Atomic Energy Commission, or some component thereof, would aspire to this role. In either event, it now looks as if there will be a great acceleration in R&D spending.

E. As pressures for capital-cost reduction have increased, the utilities have turned increasingly during the last decade (and especially during the last five years) to purchase of cheaper foreign-made equipment, such as Swiss and Japanese turbines, Swedish and British transformers, French and Italian circuit breakers. Foreign designs are frequently as good as U.S. designs, and they often make more economical use of materials. Protective legislation has been sought by manufacturers, and antidumping provisions have been invoked in the case of power transformers. But the best answer would lie in competitive costing, and in this materials can play an important role.

Future Technologies

The number of technological advances for the generation, transmission, and distribution of electric power is currently very large. Table 4.13 lists many of the alternatives.

The industry has been in a period of rapid change, characterized by the emergence of the nuclear reactor as a preferred base-load generation plant, and the gas turbine for peaking loads. Increased penetration of gas turbines, especially in the form of combined cycle plants, into intermediate and baseload generation may be confidently expected. These changes place heavy demands on MSE.

Materials for Electric Power

The materials employed by the electric power industry are extremely diverse. Major categories are shown in Table 4.14.

In addition, the industry generates materials, of which the most abundant are fly ash and sulphur (in the form of SO_2), and the most intractable is the concentrated fission-product wastes from nuclear-fuel reprocessing.

Table 4.13 Technological Advances Relating to Electric Power

Present and Near Term (10 years)	Fossil-fuel steam turbine
	• Fuel desulphurization and stack-gas treatment
	Hydro and pumped storage
	• Drag reduction
	• Underground pneumatic storage
Gas turbines	
	• Combined gas-steam cycles
	• Combined gas turbine-coal gasification plants
Nuclear reactors	
	• Light water (boiling water and pressurized water)
	• High-temperature gas-cooled
	• Heavy-water moderated
	• Breeder (several concepts)
Superconducting generators	
Ultrahigh-voltage transmission	
D.C. transmission	
Underground transmission and distribution	
Gas-insulated cable	
Technologically Remote or not viable for mass use	Magnetohydrodynamic power
Solar power	
Fuel cells	
	Geo thermal power
Tidal power	
Fusion power	
Dispersed, small generating units using fuel delivered by pipeline (e.g. hydrogen)	
Microwave power transmission	
Cryogenic or superconducting transmission	
Power storage by batteries, fly wheels, etc.	

Table 4.14 Materials Employed in the Electric Power Industry

Fossil fuels -- oil, coal, gas

Nuclear fuels -- uranium, enriched with U_{235}, in the form of oxide or carbide

Basic construction materials -- steel, concrete, aluminum, etc.

Electrical materials
- Conductors -- copper, aluminum, etc.
- Insulators
  - Gases -- SF_6
  - Liquids -- pyranol, etc.
  - Solids -- glass, plastics, porcelain, etc.
- Magnetic materials -- silicon steel, etc.

Heat-transfer materials -- steam, hydrogen, helium, sodium, etc.

Specialized materials
- High-temperature materials, especially for turbine components
- Nuclear materials (fuel cladding, neutron absorbers, etc.)

In 1971, the electric utilities spent about $5.5 billion on fuel and about $2.2 billion on the materials content of additions to plant and equipment. Both of these figures have been increasing at about 7% per year.

Materials science and engineering related to all these materials has been undertaken primarily by suppliers to the electric utilities and by government, and to a much lesser extent by the utilities themselves or by universities and research institutes. Among organizations participating in MSE are the following:

Fuel companies (oil producers and refiners, gas producers, coal companies, uranium refiners, integrated “energy” companies)

Office of Coal Research, Department of Interior (coal treatment, desulphurization, gasification, etc.)

Suppliers of electrical equipment (generally large companies with both local and central R&D organizations)

Electrical materials suppliers (e.g., silicon steel producers, insulating materials producers)

The Atomic Energy Commission (approximately $28 million annual expenditures on R&D on nuclear materials)

In addition, a number of materials developments undertaken by the aircraft industry, such as nickel-base superalloys, high-strength composites, structural ceramics, and oriented eutectics are already having impact on the electric power industry, or are likely to do so in the future.

Critical Problems in Materials Use and Development

The economic feasibility of many of the newer methods or power generation will be significantly if not critically determined by materials availability and performance. These relationships are illustrated in Tables 4.15 and 4.16.

In each of these areas, there is a clear relationship between a national objective and a specific group of materials developments. This relationship is illustrated in Figure 4.4.

Summary and Conclusions

Demand for electrical energy will continue to grow in the U.S. and even more swiftly in those parts of the world that are in the early stages of industrialization. The generation and transmission of power can be undertaken in ways that protect the environment, but substantial innovations and expenditures will be needed. Low-sulphur fuels, increased use of cooling towers and ponds, containment and treatment methods for radioactive effluents and wastes, possibly remote or offshore siting of plants and the development

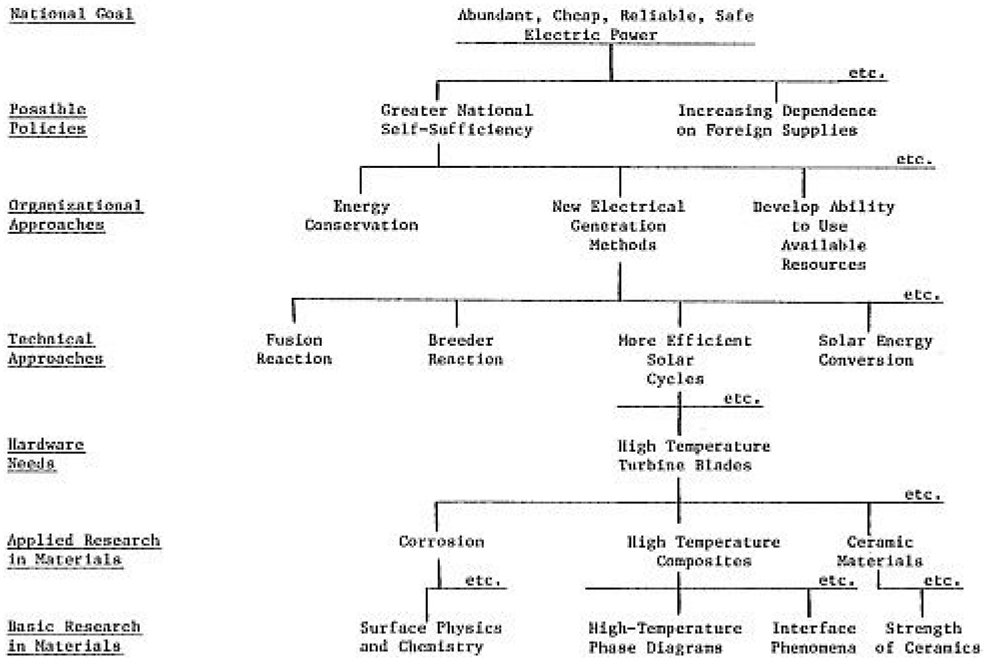
Table 4.15 Energy Developments in Which Further Advances in Technology Are Now Limited or Inhibited by Materials

Area	Problem
MHD	Life of electrode materials and construction materials at 2200° C and above
	Cost of seed materials (open cycle)
Solar power	Cost/efficiency of available solar-cell materials (present efficiencies 13% silicon, 18% GaAs)
Fuel cells	Cost and life of electrode materials (most now contain precious metal catalysts)
	Cost of hydrogen as a preferred fuel for high efficiency
Coal desulphurization	Several proposed methods all have materials disposal problems (including use of the ultimate sulphur)
Power from municipal waste	Limited by composition and properties of waste and economics of sorting

Table 4.16 Critical Energy-Related Materials Areas in Which Solutions Appear Possible, given Substantially Increased Materials Research

Area	Direction of Materials Effort
Nuclear-fuel cladding	Zircalloy, stainless steels, development of new cladding
Ultrahigh-temperature gas turbines	High-temperature ceramics, such as silicon nitride, oriented eutectics
Large (above 1200 MW) steam turbines	Limited by fabrication processes and perhaps physical properties of rotor materials
Low-cost fuel	Increased knowledge of hot corrosion materials, such as vanadium
High temperature nuclear reactors	Handling of suitable heat-transfer materials, such as sodium and helium; impurities and reactions with cladding and structural materials
New generators	High-strength composites for retaining rings; niobiumtitanium and similar superconductors for superconducting generators
New transmission cables and integrated substations	Alternative conductors, such as sodium; gaseous insulators, such as SF_6; materials performance in cryogenic environments and refrigerant materials
D.C. transmission	Silicon for bulk power devices
Power interruption	Zone-refined metals for vacuum interruption; metal oxide varistor materials
Direct buried transformers	Water-resistant casing materials

Figure 4.4 Partial Relevance Tree for Energy



of "power parks," underground transmission, increased attention to power systems, interconnection, and the resultant stability considerations; all are likely technological responses. All will add to costs at a time when the electric utilities will be under cost pressure from other sources: fuel costs, construction costs, and costs of money. One predictable result will be an increased premium on generating-plant efficiency which will make the development of ultrahigh-temperature gas turbines, combined cycle plants, and high-temperature reactors more desirable. Materials science and engineering has major contributions to make to these developments. At the same time, materials substitutions and advances contributing to reduced costs will be eagerly sought.

Materials research related to electric power will increase, and quite likely rapidly so in the next few years. Governmental pressures on the utilities for more R&D, the desire of U.S. equipment manufacturers to remain internationally competitive, the increased needs for environmental information and control technology will favor increased R&D expenditures. The source of these expenditures is not yet clear, but legislation and decisions by the regulatory agencies will be critical elements.

The whole electric power industry, and indeed all the energy-producing and distributing industries, are rapidly assuming a place in the forefront of public concern. A more explicit formulation of national goals in respect to electric power, and the strengthening and coordination of federal policy mechanisms concerned with promotion and regulation of electric power are one of the likely results. Materials science and engineering is destined to play an important part in the search for improved or wholly new power supply systems that satisfactorily combine the requirements of abundance, low cost, reliability, and compatibility with environmental standards.

Additional Note on Materials Research Problems

Industrial Processes

Energy accounts for 1–2% of the added value of manufactured machines, equipment, and instruments. However, as a fraction of the value of industrial materials produced from natural materials, energy is much larger. Some illustrative data are given in Table 4.17 (the energy is a combination of heat and electricity in most cases). The implications are clear of how research on material processes aimed at increasing efficiency of energy utilization can have a significant impact on the nation's energy consumption.

Breeder Reactor

The development of commercial breeder reactors is a major task requiring many types of contributions from many specialties. One particular material development is described to illustrate the central role of MSE in this important technology.

Table 4.17 Relation of Energy to Value of Materials

Industry	Energy Bill as % of Value
Electrometallurgical Products	17.07
Alkalies and Chlorine	20.37
Primary Aluminum	10.68
Primary Copper	13.76
Blast Furnaces and Steel Mills	20.64
Steel Rolling and Finishing	11.16
Cement, Hydraulic	22.28

Water-moderated uranium-dioxide-base fuel elements are used in both burner reactors and fast-neutron breeder reactors. Sintered UO_2 pellets, approximately a centimeter in diameter, enclosed in drawn zirconium tubing, having a wall thickness of approximately 0.5 millimeter, some 4m long, closed at the ends by welding, accurately spaced in bundles ranging from 10 to over 300 tubes and providing 20,000 to 100,000 rods per reactor, serve as the heat source in both pressurized-water and boiling-water reactors. These reactors are projected as likely to supply some 150,000 megawatts of electrical power[9] in 1980 or about 25% to 30% of the estimated demand for electricity in the USA at that time. By 1990 breeder reactors are likely to be in use, employing uranium-plutonium oxides in somewhat similar fashion, encased in somewhat smaller thin-wall tubing made of alloys perhaps resembling 316 stainless steel.

For the uranium-plutonium oxides, there are many features which must be better understood such as: (a) limits of elastic and plastic deformation; (b) fracture; (c) corrosion; (d) altering system composition; (e) diffusion; and (f) crystal defects. Moreover, these phenomena are considerably modified, by and extended to less familiar situations by: (a) recoiling ions and atoms with energies up to 120 MeV; (b) accumulation of up to 20% of about 40 different fission-product atoms; and (c) temperature gradients approaching 10,000° C/cm. The objectives of tests are to determine whether elements can produce and transfer heat amounting to at least 20 Kwd/kg (kilowatt days/kg) of contained fission material averaged over the reactor core, and at rates at least 50 Kw/m averaged over their length. More generally, the aim of the development and applied research will be to find the limits on these quantities, hopefully with factors at least 5 and 2, respectively, greater than those just listed.

Thermal performance must also be known sufficiently well for design decisions. Heat production, heat flow, temperature, and temperature gradients not only provide major constraints on the technology, but also are extensive and intensive variables having to do with the state of the system and its evolution in time. Typical heat flux to the coolant has to be in the neighborhood of 100 watts per cm^2. Heat transferred per unit length of fuel pin is directly related to the surface and central temperatures of the pin through the integral of the thermal conductivity between these two temperatures.

Utility of uranium dioxide depends on its relatively great chemical and radiation stability rather than on its ability to transport heat. Conduction in U02 is ordinarily by phonons and the minimum thermal conductivity is slightly over 0.02 w/°C cm, corresponding to a phonon mean free path of about one lattice constant. Below 1000° C the mean free path is greater, but this is reduced by induced defects and the accumulation of fission products. Above, perhaps, 1800° C the conductivity may increase due, probably, to electronic excitation processes. Very extensive measurements of the thermal conductivity and of the thermal-conductivity integral provide a basis for design and interpretation of the physical and chemical changes in the oxide. A safe and accepted central temperature permits light water fuels to have a

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[9] E.B.Tremmel and AEC Staff, The Nuclear Industry 1963, USAEC, Supt. of Documents, U.S. Government Printing Office, Washington, D.C.

thermal conductivity integral of about 50 w/cm.

Uranium nitride and carbide have much greater thermal conductivity and sufficient stability to give much larger linear ratings and therefore should be developed as fuels. Outside of some laboratory studies of chemical, physical, and radiation-induced behavior, little fuel development based on these compounds is in progress.

In addition, physical and chemical changes in the oxide fuels need to be determined, particularly as they are influenced by radiation-induced creep, swelling due to accumulation of solid fission products and growth, migration and release of fission-gas bubbles.

Finally, precise fabrication techniques, quality control and inspection procedures are required for manufactured fuel elements to meet stringent safety requirements.

High-Temperature Gas Turbines

Gas turbines, originally developed for high-speed aircraft, have rarely been used for continuous basis power generation. Until recently, they have been adopted by large electric utility companies for peaking power and to fill the gap caused by delayed additions of nuclear, and in some cases, conventional steam-generating plants. Seldom if ever have they utilized gas from the combustion of coal as the working medium because of the abrasive nature of the gas steam. Gas turbines, in principle, operate much like the old fashioned windmill. A high-pressure, high-temperature gas obtained from the combustion of a fuel, is first compressed and then expanded through nozzles onto the blade of a turbine. The rotating blades in turn drive against the torque exerted by the load, viz, a generator or pump, and additionally, its integral compressor.

For optimum results, the gas temperature should be as high as possible. Gas pressures (pressure ratio) should also be large. The thermal efficiencies of natural-gas-fuel turbines today are in the range of 25–30% when operated at temperature of approximately 870° C. An increase of gas temperature by 25° C will increase the efficiency by about 204%. It is predicted that if temperatures can be raised to 1100–1300° C, an overall efficiency of 40– 45% can be achieved. Gas temperatures per se are no obstacle. The inhibiting factor is the temperature capability of the turbine parts, heat exchangers, and associated apparatus. New or improved materials are the key to success in this area. Metals and/or ceramics are required which are oxidation-, impact-, and thermal-shock resistant, and which have high strength and ease of fabrication.

At present, materials under consideration for turbine applications include composites (SiC, and Al_2O_3 fibers in a metal matrix), Al_2O_3, Si_3N_4, and several carbides (TiC, NbC, SiC with metal additions). Property and performance data on these and other materials are lacking, particularly in such areas as: (a) strength, at high temperatures, (b) creep characteristics, and (c) thermal expansion. Of late, Si_3N_4 has been under intensive investigation for use in turbines. This material, as shown by current materials research, has good strength, low thermal expansion, unusual fabricability, and is moderately oxidation resistant. Further development, however, is necessary before Si_3N_4 or other such materials can be successfully adapted to the proposed high-temperature gas turbines.

Magnetohydrodynamic Generator (MHD)

Generation of power using MHD is not a new concept and, in fact, is based on principles outlined by Faraday 100 years ago. Basically, it operates by the motion of an electrical conductor in the presence of a magnetic field, the same principle as for the conventional rotating generator. In MHD the moving conductor is a heated fluid, gas, or liquid. In its simplest form, a hot fluid conductor is passed through a channel which has a transversely oriented magnetic field. By inserting electrodes in the fluid stream, direct electric current can be generated at high voltages. The MHD generator performs in a manner similar to that of a turbogenerator. In both cases, work is extracted from a heated fluid at the expense of a pressure drop and corresponding enthalpy decrease. In open-cycle MHD, seeded gas, normally combustion gas from the burning of fossil fuels, serves as the moving conductor. The combination of seed material (i.e., K_2SO_4) and high temperatures (~200°–2400° C) usually makes the gas electrically conductive for generator operation. These extreme conditions play havoc with containment materials and the electrical characteristics of insulators and conductors. Overall, the chamber, channel, and associated parts must resist corrosion through oxidation, erosion, and alkali attack, and must withstand thermal shock as well as extreme temperatures.

Materials capable of withstanding such severe environmental conditions are few and are primarily limited to those having high melting points. Because of oxidation problems, only pure oxides, or combinations thereof, appear to be the best candidates for open cycle MHD applications Even here, a number of oxides must be eliminated from consideration because of cost and poor properties (toxicity, hydration, vaporization, etc.). At present it is generally impossible to make a wise choice of materials for many fundamental questions are unanswered. For example, current thinking envisions stabilized ZrO_2 for the electrodes; Al_2O_3, ZrO_2, and MgO refractories for the burners; coal fuel and air seeded with K_2SO_4 as the gaseous conductor. The behavior of this combination of materials at high temperatures simply cannot be predicted with our current state of knowledge. Reliable design criteria and proper materials selection can only come about through coordinated materials research and engineering in several areas, specifically: (a) phase equilibria, (b) vaporization, (c) electrical conductivity, and (d) mechanical properties.

Solid-State Electrolyte Batteries

Environmental concerns have prompted a renewed effort toward the development of low-cost, reliable, non-polluting methods of energy conversion and storage. Electrochemical devices potentially offer an opportunity to replace the internal combustion engine in automobiles and materials research in this direction has accelerated during the last decade.

Electrochemical devices are converters of chemical energy to electrical energy and are generally categorized according to the source of energy into several basic cell types: (a) fuel cells, (b) primary cells (flashlight batteries), and (c) secondary cells (storage batteries). Cell performance is rated on (a) the amount of generated power per unit device weight (specific power in watts/unit weight) and (b) capacity to store energy (specific energy in watt-hours/unit weight). Because of attempts to maximize specific power and specific energy, a large array of new materials are being investigated for application as electrodes and electrolytes in electrochemical devices.

One of the most promising electrochemical secondary cells recently developed is the sodiums-sulphur battery. In this device, liquid Na serves as the anode and liquid S (in contact with carbon felt) as the cathode. The central feature of the cell, and the primary innovation, is the solid-state electrolyte, beta alumina ($\sim Na_2O \cdot 11Al_2O_3$), whch allows unusually high transport of alkali ions. When the cell is connected to an external load, electric current is produced via diffusion of Na ions through the electrolyte according to the reactions:

$Na \rightarrow Na^+ + e^-$ (anode)

and

$Na^+ + e^- + S \rightarrow Na_xS_y$ (cathode).

Recharging of the battery is accomplished by a reverse process: Externally supplied current causes Na-ion-flow in the beta alumina electrolyte, eventual ly returning the Na and S electrodes to their original states.

Although the beta-alumina Na/S battery can be considered a significant advancement, it is not yet the answer to electric vehicle propulsion. Limiting aspects of the battery are the high-operating temperature (~300° C) and the crystallographic restriction of two-dimensional alkali diffusion. In addition, the presence of sodium in the metallic state poses a real hazard in the event of a crash. New materials must be developed to overcome these faults as well as improve cell output. Basically, the nature of the problem is crystallographic and involves the search for materials with abundant charge carriers of very high mobility in three directions. Importantly, mobility apparently is a direct consequence of positional disorder of the charge carriers. For example, the hexagonal structure of beta-alumina is made up of spinel-like blocks separated by bridging planes composed of Na, Al, and O ions. It is along these planes that Na ions have a high ionic conductance. This structure only typifies that needed for an effective solid state electrolyte. The ultimate solution (if any) probably may be found in entirely different classes of structures.

Superconducting Materials

In the generation and distribution of electricity, a rough rule of thumb is that 50% of the cost goes to generation of electricity in the central plant, 40% of cost is for distribution at the local level, and 10% is required for distribution at high-power levels. In special situations, such as large urban centers where space is at a premium, the transmission costs for high energies may go up by as much as a factor of five.

In the generation of electricity by rotating machinery, the tremendous advances in superconducting materials of the past few years may yield substantial improvements in efficiency. The limitations of efficiency in present generators is due in part to the intensity of the magnetic field which can be produced by a given volume and weight of normal electrical conductors. In turn, the volume and weight limitations come from the material strengths avaialble to support large rotating masses. Superconducting alloys have been developed which will, in suitable coil form, produce very large magnetic fields. In principle, this should provide a substantial increase in efficiency of electrical generation. In practice, however, there remain difficult and fundamental material problems to be resolved. The new alloys which will support large magnetic fields are lossy in the presence of changing fields. Present developments using superconductors in rotating machinery utilize the superconductor in a situation which minimizes its exposure to changing magnetic fields. For example, the superconductor is imbedded in a copper-nickel alloy which is deliberately made lossy so that eddy currents are increased and the superconductor is shielded from the changing magnetic field. Because of the requirement for nearly constant magnetic fields at the superconductor site, its use is limited to either the stator or rotor but not both.

Progress is being made on reducing the AC losses in the high-magnetic field-type superconductors. Considerably more work needs to be done of both a fundamental and engineering nature. An important aspect of the problem is the requirement to make large-scale machines and to run extensive high-power experiments. The practical problems involved in applying superconductivity to electrical generation do not scale in any simple way. The power companies, of course, are interested only in large-scale generators, but full-scale models are very expensive to construct and evaluate. There are difficulties in applying technology to full-scale production; this is a case in point. Certainly the entire power generating industry in the U.S. is of sufficient magnitude to warrant a considerable investment in development of more efficient generating machinery. New ways of allocating costs of development between the companies and the customers need to be explored to provide a suitable framework for exploitation of technology in this area.

In situations where high power must be transmitted underground and particularly where ground space is expensive, the superconducting cables offer an advantage. The potential savings come not from avoiding the generating cost of the heating losses in the cable but rather in the problems of dissipating the heat which is generated in confined spaces. With superconductors, there is essentially no heat generated along the cable and the added problem of providing cryogenic cooling is more than offset by the savings in avoiding heat dissipation.

This application will also require considerable materials research. Extensive use of superconductor calbes would require very large inventories of helium for the cryogenic material. For the long-range future, it would be prudent to avoid this critical material problem by developing a superconducting material which can operate at temperatures achievable by liquid hydrogen cooling. Theoretical understanding of the relation between composition, structure, and critical temperature of superconductors is insufficient to say whether nature will allow achievement of this goal.

A practical problem in the application of superconductors to high-power transmission cables is the forming of joints in the field. Welding, with its high-temperature cycle, tends to destroy the very state of the material which was created to make it superconducting. This practical problem is likely to require an extensive research effort. Another practical problem concerns making the superconducting cables sufficiently flexible so that large rolls can be transported to the installation site, thereby minimizing the need for field joint construction.

TRANSPORTATION AND MATERIALS NEEDS

To illustrate the role of transportation in the nation’s economy, may point to the 15% or so that consumers spend on it out of their personal consumption expenditures or to the fact that all expenditures related to transportation represent about 20% of the GNP.[10] But because more than half of these expenditures are intermediate and thus hidden in the cost of the final product, or are carried under other headings (e.g. insurance companies), transportation as an industry accounts for less than 5% of aggregate national income as defined in U.S. national accounts. The 15 to 20% range thus conveys a better idea of the role of transportation.

Because we tend to talk often in terms of a “transportation crisis,” we are led to believe that transportation has been a steadily growing fraction of GNP. Actually, that fraction has remained remarkable stable: the comprehensive estimates prepared annually by the Transport Association of America show that between 1958 and 1970 the nation’s “freight bill” as a percentage of GNP has trendlessly fluctuated in the narrow range between 9.6 and 9.1%; the corresponding percentages for the nation’s “passenger bill” were 10.2 and 10.8, again without a trend. Our impressions thus are due to the fact that so many more of us meet the “transportation problem” in its most intractable forms, e.g., street and highway congestion and air pollution.

While the growth of transportation expenditures has paralleled that of the economy, its different segments have grown quite unequally. Estimates comparing the late 1950’s to the late sixties show rail expenditures advancing by only 10, marine by 64, automotive by 77, and air by 166%. None of these magnitudes begins to measure the impact that the motor vehicle alone has on the American economy, in terms of goods and services associated with it directly or indirectly. Yet, President Kennedy’s assertion in his Transportation Message of 1962 that national policy in the field of transportation was a “chaotic patchwork of inconsistent and often obsolete legislation and regulations” probably is still accurate today, despite the fact that there now exists a Department of Transportation and federal outlays have doubled in the past decade, primarily investments in capital facilities. Highway construction grants-in-aid to states account for about 60%, support for aviation 20%, rails 5%. But it would be difficult to prove that the construction of a

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[10] Transportation Association of America.

large interstate highway system is part of a comprehensive and internally consistent national transportation goal. Indeed, these highways have often produced grave problems for the cities onto which they unload their traffic.

Urban transportation is now dominated by the automobile, with 90% of urban travel accounted for by the private passenger car. While city streets comprise only 14% of total mileage, it is estimated they accommodate over half of the total national travel as measured in vehicle miles.

Changing Goals in Transportation

Historically, U.S. policy has sought to keep the modes of transportation separate and to afford a measure of protection to both the investor and the user from exploitation by either cutthroat competiton or unregulated monopolies. Railroads, for example, are not generally permitted to provide trucking service or own a trucking enterprise. This and other basic regulations, e.g., requiring that common carriers provide service upon demand at non-discriminatory rates, stemmed from the view that railroads constituted a monopoly and that, without regulation, monopolies tended to leave the public without protection, both as investors and as consumers. Detailed regulation was provided by the Transportation Act of 1920.

Other common carriers were similarly regulated through legislative enactments down to and including the Act of 1940. However, many exceptions in various legislative acts have sanctioned the growth of much traffic outside of the control pattern, and, of course, the private automobile, as opposed to the public carriers, was subject to no regulation whatever, while even with the emergence of competitive means of transportation, railroads remained subject to strict and often cumbersome regulation. The shift of traffic to private carriers, to pipelines, and to trucks, coupled with various types of subsidies to motor and air transportation, resulted in the gradual deterioration of both the railroads and the maritime industries. Instead of moving toward a coordinated system in which each mode was used in its most efficient way (e.g., rails for long-haul bulk movements and for short-haul, high density commuter traffic) the different branches were treated as different industries.

Yet, most recent trends both in legislation and federal spending clearly indicate a desire to establish a “balanced transportation system” and at the same time to minimize the adverse effects on the environment. (See Table 4.18.) The High Speed Ground Transportation Act of 1965 was aimed at improving intercity rail service, following President Johnson’s call in his 1965 Message for 100-mile-per-hour railroad passenger facilities between Boston and Washington. Urban transportation has been identified as a top priority area. In Fiscal Year 1971 some $400 million was obligated by the Urban Mass Transit Administration in the form of grants to municipalities for capital assistance, technical studies, demonstrations, and R&D; about $33 million of this sum was obligated on direct contracts for research, development, and evaluation. The Federal Highway Act of 1970 has established a new urban highway program with emphasis on highway-using mass transit systems. It is estimated that $17.7 billion will be spent for rapid transit systems in U.S. cities during the 1970’s.

With regard to managing noxious emissions from transportation media,

Table 4.18 Major Events in Transportation Legislation

Date	Act	Theme
1926	Air Commerce Act	Directed Secretary of Commerce to promote air commerce and regulate it in interest of safety.
1938	Civil Aeronautics Act	Recognized need for national system of airports.
1946	Federal Airport Act	Provided national plan for development of public airports
1956	Interstate and Defense Highways Legislation	Provided nation-wide energy system.
1961	Housing and Urban Development Act	Provided emergency loans for urban mass transportation.
1963	Clean Air Act	Research on motor vehicle exhausts.
1964	Urban Mass Transportation Act	Federal funds for UMT systems.
1965	Clean Air Act Amendment	Established federal standards for auto exhausts.
1965	High-Speed Ground Transportation Act	Research and Development for intercity rail transportation.
1966	Urban Mass Transportation Act Amendment	Research program for improvement of UMT
1966		Office of Noise Abatement (later renamed Office of Environmental Quality) formed in FAA.
1966	Department of Transportation Act	Department of Transportation formed combining seven agencies concerned with air, ground, and water transportation.
1970	Urban Mass Transportation Assistance Act	Recommended $12 billion expenditures for UMT over 12 years. Authorized $3.1 billion starting in fiscal 1971.
1970	Railroad Passenger Act	Established “Railpax.”
1970	Clean Air Act Amendment	Stringent regulation of auto exhausts commencing 1975.
1970	Airport and Airway Development Act	Established minimum safety standards for airports for 1972.
1970	Federal Aid Highway Act	Demonstration for elimination of rail grade crossings, encourage highway-using mass transit system, greater federal support for primary and secondary highway construction.

Clean Air Acts have established controls on automobile exhausts; the Airport and Airway Development Act of 1970 has set minimum standards of safety for airports; and the Federal Aviation Authority now has an Office of Environmental Quality, which concerns itself with engine-exhaust pollution, aircraft waste and smoke emissions, and aircraft noise. The concern of the public for reducing pollution and for greater safety will clearly influence the direction of future developments in the transportation industry.

A Spectrum of National Goals in Transportation

It has been pointed out earlier in this chapter that one does well to think of a wide spectrum of kinds of goals as well as of a ranking. This can be illustrated particularly well in transportation. There are large, discrete tasks such as the building of urban mass-transportation systems in San Francisco, Washington, Seattle, Atlanta, Baltimore, Los Angeles, Miami, Minneapolis, Pittsburgh, and other major cities. There are complex, open-ended programs such as the improved coordination of the modes of moving goods by land, sea, and air. There are large research, development, and engineering tasks with great social utility like the elimination of atmospheric pollution from internal combustion engines; and others of uncertain outcome or merit such as the supersonic transport or nuclear propulsion. Better transportation can be the vehicle for correcting social deficiencies; it can improve productive performance; and finally there are goals which require specific inventions—more efficient batteries, fuel cells, aircraft nose suppressors, etc.

Major Impacts of Technology on Transportation

Transportation systems consume such enormous quantities of materials— metals, concrete, plastics, etc.— that any advance in MSE is apt to affect transportation and cause shifts in relative costs. A major change in energy generation or distribution technology may also have a profound effect on transportation—through altering the possibilities for propulsion or through providing in a different way for the dissipative losses associated with friction. The greatest recent advances in moving goods and people have probably resulted from the application of solid-state devices to information and communication systems utilized in transportation-system control. At first glance this would not seem a fruitful area for MSE until we estimate some of the trade-offs, e.g., between time and fuel loss at intersections and better traffic control by means of solid-state devices and integrated circuits, which depend in a highly sophisticated way on materials; or between improved reliability through control-element redundancy and the weight and cost of the extra controls which would be required.

We shall look briefly at the important role which materials substitution has played in the development of our transportation system. An outstanding example is aluminum. Without it, large-scale air transport would not have been achieved, and conversely one might argue that without significant growth of the aircraft industry, aluminum might still be a relatively little-used material, although by now that industry consumes only 3% of all aluminum marketed in the U.S. However, while materials developments can facilitate improvements in all systems, the major developments will be primarily limited by the absence of political or social decisions rather than by materials. The non-polluting automobile is a possible exception. One solution, for example, may be an electric automobile, but satisfactory low-cost battery materials are not presently available. Technologically, silver-zinc batteries could be used in a limited-range electric car, but the high cost of the necessary silver would exclude a mass market. An experimental version of such a car, built by General Motors in 1966, required 680 pounds of silver and zinc. The essential requirement is for a relatively low-cost battery system having a specific power of 100 watts/lb. and capable of producing 100 watt-hours of energy/lb. The best present candidate is the high-temperature sodium-sulphur battery; room-temperature electrolytes are clearly needed. High-cost materials also remain a primary factor against the fuel-cell-powered automobile. Materials take on a special significance in the automobile industry with its annual raw material consuption worth $5 billion.

In the following, we comment on certain materials technologies which are related to ground, sea, and air transportation respectively.

Materials Technology for Ground Transportation

Materials technology, both for metals and plastics, is important in providing proper light-weight structures—for locomotives, for transit cars, for trucks and cars. It includes prediction of the fatigue and failure life of materials—essential in view of the service characteristics and long life of transportation equipment. Metal and plastic parts must be carefully screened for fatigue resistance because of the occurrence of cyclic forces, or random high-acceleration forces.

Although some advantage might be realized from more advanced materials throughout the product lines, in general the main requirements are met by state-or-the-art materials. However, there are interesting and important requirements for specialized subsystems such as electrical controls, storage-battery components, electrodeposited finish systems, etc. Nonsmoking, self-extinguishing polymers are now required by law for application in public transit systems. Lower-cost electrical insulations are a goal; the choice of present resin systems requires considerable tailoring with concern centering on flammability and smoke behavior as well as on dielectric strength, life, etc.

One of the most important areas for advances in transportation materials technology lies in the development of solid-state power components. As rail vehicles speed and power requirements increase, the trends in propulsion will be toward increased electrification and toward the use of A.C. traction motors. Technical challenges are in three areas:

a. Energy transfer, e.g. from the power-system grid to the moving vehicle and in reverse for braking, the latter being particularly important for achieving cooler subways.

b. Power conversion and control on board the vehicle, with the power being transferred from the grid or generated on board by a prime mover.
c. Propulsion units, either rotating motors for wheeled application or linear motors for future air-cushioned vehicles—or for magnetic suspension vehicles.

While we cite challenge areas using examples from mass transportation, it is also likely that solid-state power components based on silicon technology will increasingly find important use in other vehicle types.

Materials Technology for Marine Transportation

On the assumption that for the forseeable future, ship propulsion will continue to rely upon the most inexpensive residual oils, whether for the boilers of marine steam turbines, in marine diesel engines, or in gas turbines, the materials problems will involve hot corrosion in the presence of sulphur and some components of ash, such as sodium and vanadium, and also ash deposition. Problems of this kind are being explored by the Maritime Administration in cooperation with marine equipment suppliers. In contrast, the problems associated with nuclear ship propulsion lie in a somewhat more remote future. Present programs and experience in nuclear fuel materials technology will no doubt contribute solutions here, and the relation of this work to national transportation goals, involving a substantial ship construction effort in the next two decades, must not be overlooked, as it affects both fuel supply and environmental impact, in this case on ocean ecology. For the present, however, corrosion resistance may be the most important material property in marine propulsion, where salt-containing air and fuels combine to form a very hostile atmosphere.

Materials Technology for Commercial and Military Aircraft

Among technologies that are critical to improved aircraft engines, with increased thrust-weight ratios which will permit greater payload, composites are at the head of the list. Low-temperature (up to 315° C) composites of high-performance filaments and high-temperature composites for 1100° to 1375° C service are both important.

Low-Temperature Composites

All aircraft-engine manufacturers appear to believe that carbon-or graphite-reinforced polymers will be the eventual winner for low-temperature fan applications. Rolls Royce's overly accelerated effort to put this material into their RB-wll contributed importantly to financial problems but these materials are potentially important in lowering engine weight. In time, modifications will be required for the higher temperatures that will be encountered in higher-speed, multi-stage fans. Blade tips in the second and third stages of such fans may encounter temperatures as high as 315° to 480° C, in which case, higher-temperature polymer matrices may be required.

An alternate material is boron-reinforced aluminum. This is an important back-up to graphite fiber/polymer composites, because it is less anisotropic and is superior in erosion and impact. The aluminum may also have slightly greater temperature capability than the carbon-polymer materials.

An extensive “Composites Recast” NASA/Air Force study completed in the Spring of 1972 concludes that the utilization of composites (mainly polymer-and aluminum-matrix) is inhibited by cost and by lack of confidence. The high cost results from the small volume of business, lack of operational experience, and lack of data on the economics of high-volume production. Confidence is lacking due to (a) inadequate basic data and understanding of failure modes, (b) lack of data on properties versus life in various environments, and (c) penalties in performance due to such design requirements as holes, attachments, abrupt changes in contour, etc.

High-Temperature Composites

A second area for which composites hold promise is in high-temperature materials for use in the turbine section of a jet engine. High strength, high dimensional stability, excellent oxidation resistance, low density, and an operating capability above 1100° C for thousands of hours are required. Major problems in achieving these goals by means of synthetic composites are (a) the choice of filaments and matrix that are chemically compatible over long times, and (b) fabrication difficulties. One way of overcoming these problems is through “natural composites” in which the reinforcing and matrix phases are produced automatically in certain favorable cases by carefully controlling the solidification conditions. These composites are capable of providing a major advance in high-temperature materials.

A large ARPA program is also underway to develop ceramic turbine components. The emphasis is on the use of Si_3N_4 and/or SiC. Considerable progress has been made toward small integral Si_3N_4 blades and disk for automobile use. There is some skepticism about the applicability of such brittle materials in aircraft engines because of vulnerability to impact damage.

Oriented Eutectics

Metal eutectics, which may be viewed as composites formed naturally during properly controlled solidification of appropriate compositions, offer the possibility of significantly increasing the maximum material temperature in gas turbines. One especially attractive composition is a cobalt alloy reinforced with TaC.

When composites of the kinds we have mentioned become more widely used in engines, new modes of deformation and failure will be encountered. It will be important to understand the relationships among stress, strain, temperature, and cyclic frequency, and to be able to forecast failure in these materials.

Future jet-engine turbine buckets undoubtedly will be coated by materials which extend the life by providing environmental resistance and improve performance by maintaining a ductile surface to inhibit crack initiation. The latter will be of particular importance if one goes to more brittle materials. New ultra-hard synthetic materials have demonstrated substantial improvement over conventional carbide tools in the machining of jet-engine superalloys. Other new techniques, such as a plasma torch or laser beam used in conjunction with new tool materials, may offer significant promise for further improvement in the machining, drilling, or shaping of the materials for aircraft engines. Other opportunities may develop from (a) electrochemical machining of titanium and nickel-base alloys, (b) extension of the capability of laser drilling with high-powered lasers, or (c) ultrasonic assistance in machining materials.

Figure 4.5 shows the relevance between certain specific air transport objectives and selected materials problems we have touched on above.

We have focussed primarily on the material needs for aircraft propulsion, i.e. engines. One could extend this discussion of material needs into other areas of air transportation where R&D are both active and necessary.

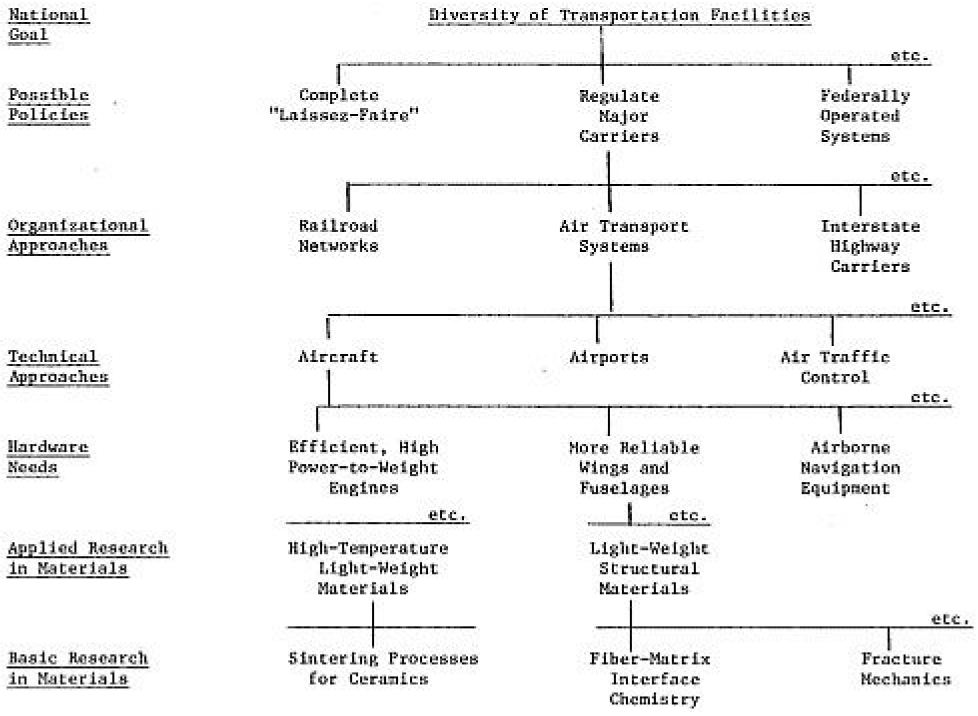
Conclusion

Since air transportation has presented the greatest technical challenges in this century, and since defense needs have given an enormous impetus to innovation and performance improvement, the amount of research and development has been higher relative to total effort than in other segments of transportation, with correspondingly greater results. In terms of its comparatively small role in the U.S. economy, this heavy concentration of R&D is indeed noteworthy. In 1969, air transport moved less than 0.2% of all domestic intercity freight (in ton-miles), accounted for less than 10% of all intercity passenger traffic (in passenger-miles), employed 13% of all those working in the transportation industry, and occupied an important role only in operating revenue (which, of course, omits all nonpublic modes of transportation like the private automobile), where it accounted for not quite 20% of the total.

In this context, the role of R&D (in the aggregrate, not for materials) in transportation other than air must appear miniscule: for 1968 NSF data show 23,900 man-years of R&D scientists and engineers applied to “motor vehicles and other transportation equipment” (excluding aircraft) compared to 93,900 for “aircraft and missiles.” Moreover, in the first category, one-quarter is located in federal establishments, as against three-quarters in the second category. In terms of funds, “aircraft and missiles” group in 1969 received 3–1/2 times that of the “motor vehicles, etc.” group.

What is important to stress here is that the goal of a “balanced transportation system” would seem to imply a move toward more balanced R&D expenditures. But differences in the source of funds as well as the typically less critical nature of materials in ground transportation—and especially in private, passenger-driven transportation—as compared to political and social issues and decisions, pose a tough challenge to the materials community. It consists in identifying those technological impact areas where advances would make an early contribution to the achievement of the “balanced transportation system” that seems to be on everybody’s agenda but has so far eluded a firm

Figure 4.5 Partial Relevance Tree for Transportation



grip by politicians, economists, and technologists alike. Those addicted to spotting trends might add that concentration on where the wheel squeaks worst—i.e., the automobile and urban transportation generally—is slowly gaining over previous concern with the more exotic modes of transportation, such as hydrofoils, air-cushion vehicles, monorails, electronic highways, etc. Not that these are to be forgotten, but early payoff with massive impact appears to be an emerging objective that must also set the sights of the community.

HEALTH CARE GOALS AND MATERIALS NEEDS

Changing National Health Goals and Institutions

In the long perspective of history, our national view of health service has evolved from that of a private relationship between physician and patient to that of a natural right of citizenship applicable above all to the aged and to the poor. If one looks for a specific turning point, the year 1965 marks the transition, but there were preceding signs of that development. Since 1965 rapidly unfolding events, both political and economic, have served (a) to reinforce the view of medical care as a “natural right,” and (b) to create the environment for substantial change in the professional practice of medicine. Medical research, at one time supported as the key to improved medical service, has taken second place behind the improvement and delivery of general medical service. Table 4.19 provides a checklist of important benchmarks in public policy formation.

The role of the Public Health Service (PHS) best reflects the changing goals. Established in 1789 to provide for the health needs of merchant seamen, it took 80 years before it became the national agency to implement national programs in control of communicable disease and epidemics. Beginning in the mid-1930’s, it was charged with the administration of the maternal and child health provisions of the Social Security Act. A decade later, the Hill-Burton Act of 1946 gave the PHS the task of allocating to the states funds for the construction of hospitals and for medical research facilities, followed within another decade by the National Health Survey of 1956, which instituted educational grants to ease the shortage of physicians, nurses, and other health personnel.

The PHS also came to administer numerous programs in areas of health research, mental health, environmental health, and consumer protection. By 1970, health R&D enjoyed third place in the national R&D list of priorities. But in 1965 the national health goals were deamatically changed by programs instituted under the Social Security and Welfare Administrations. In that year, the Medicare and Medicaid amendments to the Social Security Act of 1965 committed the federal government to finance medical service to the aged and to the poor. Inflation of medical costs rapidly boosted the cost of the program from $5.5 billion dollars in 1967 to $14 billion in 1971. Coming during a period of large budgetary deficits, inflation, and persistent unemployment, the expanding fiscal burden of Medicare and Medicaid is troublesome both to the Administration and to Congress because it seems relatively uncontrollable

Table 4.19 Changing National Objectives and Priorities Concerning Health Care—Key Documents

A. Legislation

Date	Act	Theme
1935	Social Security	Maternal and child health service
1937	National Cancer Institute	First of NIH
1946	Hill-Burton Act	Hospital construction
1956	National Health Survey	Health care survey
1956	Health Research Facility	Health research—construction
1963	Health Professions Education	Medical school—construction
1964	Nurse Training Act	
1965	Social Security (Amendment)	Medicare—Medicaid
1965	Regional Medical Program	Heart disease, cancer, stroke reg. ct.
1965	Health Professions Act	Medical school—scholarships
1966	Allied Health Act	Technician—scholarships

B. Recent Reports, Messages, etc.

1967	Report, National Advisory Committee on Health Manpower—need for national health system.
1968	Report, Cabinet Committee on Price Stability—suggests prepaid group practice of medicine.
1969	Message—Economic—improve efficiency of medical industry.
1970	Report—Secretary HEW—National Health Care Strategy—Egeberg calls medicine a "cottage industry."
1970	Veto—Hill-Burton Appropriation—less hospital construction, more ambulatory care.
1970	Message—Budget—expand Hill-Burton to provide out-patient care.
1970	Statement—Welfare Reform—program to replace medicare.
1970	Message—Legislative—Health Services Improvement Act (sent in February).
1971	Message—State of Union—preventative medicine, more physicians.
1971	Message—Budget—ambulatory care, more physicians.
1971	Message—Special—Health Strategy Proposal—asks for funding for HMO.

without unpopular restrictions on the 1965 eligibility criteria. The result has been a critical examination of the medical service industry.

Instead of curtailing Medicare and Medicaid eligibility, attention is being directed toward options which would achieve cost control through improving the efficiency of health care delivery. Thus, the years since 1967 have witnessed an increasing public discussion through Presidential Commissions, Cabinet Committees, National Health Strategies, and State of the Union, Legislative, Budget, and Special Messages to Congress, all of which assert that the chaotic medical service industry must be improved and above all systematized.

The Report of a Commission on Health Manpower (1967) observed that "…medical care in the U.S. is more a collection of bits and pieces than an integrated total system in which need and efforts are closely related."

The report of a Cabinet Committee on Price Stability (1968) called for the expansion of group medical practices, especially prepaid group practices, as a means of reducing the steep rise in the cost of medical services. In publicly initiating the Nixon Administration's efforts at health service reform, the then Assistant Secretary of HEW referred to the present system as a "cottage industry." As of mid-1972, ten different national health insurance proposals were before Congress, three of which call for some legislative restructuring of the health-care delivery system. In addition, the Administration, through HEW, is encouraging a voluntary restructuring of the system by the formation Health Maintenance Organizations (HMO's). In his Special Health Message to Congress (February 1971), the President asked for $22 million to assist in setting up HMO's, for $60 million to expand medical schools, and for amendments to the Health Profession Loan Program which would provide for loan forgiveness to graduates serving in underserved communities.

The Nixon Administration, as did the 1967 report, drew substantially upon the experience of the Kaiser-Permanente Program, a private system centered on the West Coast, which is the largest non-governmental healthcare delivery system in the United States. Through its participating organizations the Kaiser Foundation Health Plan, Inc., the Kaiser Foundation Hospitals and the six Permanente Medical Groups, the Program organizes, manages and provides medical, hospital and related services to more than two million subscribers and their dependents in five states. The Program now includes services in 21 hospitals and 54 medical office-clinic facilities for ambulatory care, by about 2000 physicians organized in six regional groups, at an average annual cost of $450 per family.

The Administration has set a goal of 450 HMO's by 1973, with 100 located in presently underserved communities. By 1976 the plan calls for 40 million people enrolled in 1700 HMO's, one-fourth from families with incomes below $8,000.

Along with the thrust toward improvement of the medical services, the last decade has seen several medical research programs initiated within the purview of The National Institutes of Health: the artificial heart program at the National Heart and Lung Institute (1964); the artifical kidney program at the National Institute of Arthritis and Metabolic Disease (1965); and the cancer program, though established in 1937, with a tremendous boost from a three-year authorization of $1.6 billion and a certain measure of independence from NIH (1971). In spite of these new programs, the federal health research budget, which rose from $87 million in 1955 to $1.4 billion in 1967, has remained virtually level as attention shifted from health research to health care delivery. The exception has been the new attention to cancer research.

Until inflation comes under control, rising Medicare and Medicaid costs, because of their impact on the federal budget, will continue to be a major consideration in the determination of health care policy and will tend to depress expenditures for research. Materials science advances in the health care field will therefore be more likely to be conditioned by market forces than by growing federal expenditures for biomaterials research.

The Structure of the Health Care Industry— Present and Planned

Health care is a $67 billion industry in the U.S. making it the nation's second largest, with 80% of the spending divided equally between government and private consumers; private insurance carriers are responsible for the balance. Health care services account for 80% of demand with drugs, construction, professional equipment, research, etc., accounting for the remaining 20%. Growth has been rapid and continuous.

Health care expenditures rose at an average annual rate of 8% prior to 1965. Since passage of Medicare and Medicaid legislation in that year, they have risen at 12%.

Though a greater fraction of GNP is spent on health care in the U.S. than in other industrialized nations having national health coverage, the existence of an estimated 40 million Americans who currently receive little or no care added to anticipated population growth in the next decade could increase service demand by some 30%.

Governmental initiative will become the major driving force in reshaping our health delivery "system" in such a way as to enable it to meet the growth in demand; but as the government also becomes the major source of care spending, it will increasingly come to feel the fiscal burden, which is not under the discipline of annual appropriations, and may seek ways to restrain growth.

The national health strategy which these trends seem to be producing calls for the development of a system that recognizes the existence of a physician shortage which cannot be corrected in time to meet national needs. Thus, the strategy is aimed at increasing the service capacity of available physicians and thereby extending health service to a growing population while slowing the increase in per capita cost. This strategy is to be implemented by government action in the following areas all of which will have an influence on the medical market and the materials used by it:

a. Health Maintenance Organizations (HMO) —Federal support of HMO's is growing, with HEW producing and distributing manuals and guidelines for the organization of large group practices, including hospitals, clinics, and laboratories, capable of delivering comprehensive health care and comprehensive medical record-keeping. Specific means of federal support are (i) planning and study grants,

(ii) operating grants for HMO's in underserved areas, and (iii) grants to medical schools involved in HMO's.

b. Ambulatory Care—Hospital construction funded under the Hill-Burton Act will soon give way to federally funded facilities for ambulatory care and rehabilitation. Per diem rates in these facilities are below those of hospitals and, within an HMO, the per capita bed requirement is half that prevailing at present.
c. Prepaid Fees—HMO's will be financed by fixed annual "capitation" rates, replacing the present fee-for-service, and requiring HMO's to maintain the subscribers' health through regular examination and early diagnosis. The HMO will seek to improve its efficiency by greater use of so-called Allied Health Professionals, and improved medical and management procedures. HMO's will, in effect, compete with one another for subscribers.
d. Redistribution of Medical Service—Loan forgiveness clauses in medical scholarships, as well as HMO grants, will be employed to attract service to presently underserved areas.
e. Health Maintenance Contracts—Medicare and Medicaid service are to be purchased by health maintenance contracts instead of the current fee for service, The sums involved represent about 23% of the total health service market, and can be used to influence not only the organization but also the standards of the health industry.

Supplies and Materials

The association between specific goals and materials is less obvious in the field of health care than, say, in transportation or power generation, and this becomes more so, the more emphasis shifts from disease-specific to general health care goals. To demonstrate that an association exists, however, Figure 4.6 attempts to illustrate the derivation of materials goals from health care goals, though it stops short of the final link that establishes a material. Rather it terminates in types of apparatus, instruments, devices, or general classes of materials.

As shown in Table 4.20, the bulk of consumer expenditures for materials come under the categories of Hospital Supplies (15%), Drugs (10%), Equipment (3%), and Consumer Products (1%). Following the definitions adopted for the present study, Drugs and Consumer Products will not be discussed except to the extent that the organization of the entire industry is involved.

The distribution of spending for medical materials is best seen in Table 4.21 which indicates the sales in different areas during 1970 and, where available, current rates of growth. Medical materials may be classified in the following way:

a. Support Materials: used in general components of medical equipment and facilities.

Figure 4.6 Partial Relevance Tree for Health Services

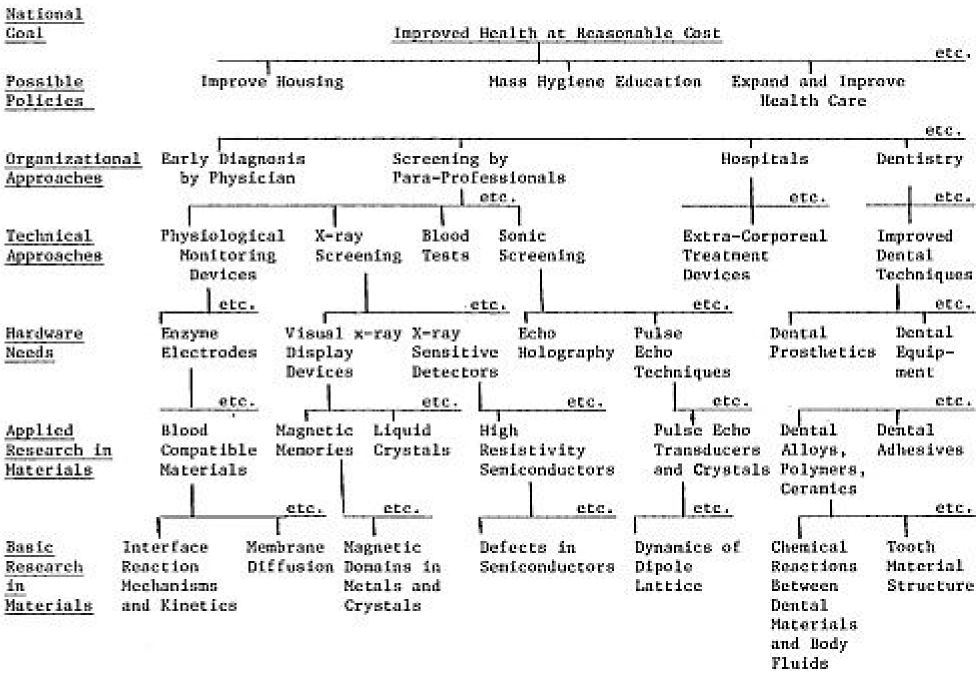


Table 4.20 Distribution of National Expenditures for Health Care

	For Health Care (in percent)	
Category	Service	Materials
Hospital Care	23	15
Construction	2.5	2.5
Drugs	0	10
Physician	19	0
Dentist	6	0
Nursing Home	4	0
Consumer Products	2	1
Research	3	0
Professional Medical Equipment	0	3

Table 4.21 Materials for Medical Care—1970 Sales and Growth Rate

	1970 Sales (millions $)	Annual Growth Rate (%)
Drugs	7,000	7
Construction	2,200	6
Surgical Supplies—disposable	300	8
Surgical Supplies—syringes, needles, sutures**	280	17
Hospital Furniture	280	5
Consumer Products	254	5
Dental Supplies**	250	
Diagnostic X-ray Equipment**	220	10
Diagnostic X-ray Supplies	220	10
Surgical Suite Equipment	200	6–15
Clinical Laboratory Supplies—reagents*	200	17
Dental Equipment	170	9
Hearing Aids	160	8
Cardiovascular Equipment * **	127	16
Clinical Lab Equipment	120	17
Clinical Laboratory Supplies—glassware	50	
Radioisotopes	36	
Diagnostic Screening Equipment	30	
Nuclear Medicine Equipment	25	17
Catheters	24	
Artificial Organs* **	22	10–20
Heart-Lung Apparatus**	19	15
Therapeutic X-ray Equipment	15	7

* See Table 4.22 for further breakdown.
** Materials advances considered to be crucial in these areas.

b. Sensory Materials: essential elements in equipment which collects, converts, transmits, and records medical information. Usually sold as part of a larger apparatus.
c. Biomedical Materials: serve in temporary or permanent contact with human tissue or fluids.

Support and sensory materials are usually developed and evaluated outside of the medical research establishment by manufacturers whose scope and activities transcend any particular user industry. Sensory materials unique to medical instruments are developed by the instrument manufacturers to protect their markets.

Biomedical materials vary sufficiently in sales volume and associated business structure to permit a division into two classes. The first includes surgical supplies (sutures, etc.) and dental supplies (cement, etc.). Each of these sold between $250 and $300 million worth in 1970. The supplies are produced by aggressive drug and dental supply firms whose development efforts are highly proprietary in accord with the potential market. On the other hand, relatively small volume has kept down industrial research in specialized biomaterials such as cardiovascular equipment ($12 million); catheters, artificial organs, and heart-lung equipment, each with a 1970 market of $20–25 million. These four categories employ materials developed for purposes other than medicine, but innovative manipulation of silicone rubber, dacron, nylon, PVC, methacrylates, acrylics and hydrogels, a variety of vascular replacements, heart valves, ozygenators, etc., has met with varying degrees of success. Orthopedic applications of industrial titanium, vitallium, and 316 stainless steel have also become customary. To be sure, certain firms supply "medical grade" metals and plastics, but since standards tend to be poorly defined in the biomaterials field, this term is far from precise and subject to some controversy.

A major problem in biomedical materials is the insufficiency of agreed standards of evaluation. One specific handicap is the dependence upon the surgical branch of the health care industry for materials evaluation. This system is not designed to maintain the comprehensive postoperative medical histories required for materials evaluations in the improvement of surgical implants.

Biomaterials Future

Continuous progress in biomaterials has been slow since most funded schedules have emphasized short-range device developments rather than longer-range work on gaining knowledge on how the adverse in-service reactions occur. Moreover, although strong industrial interest must be sti-ulated to overcome the negative effect of small volume, and ways be found to meet the problem that such sales volume precludes these companies from doing the needed basic research, further biomaterial research is still so much in its infancy that neither quantitative environmental parameters nor quantitative figures of merit for devices have been defined. Much needs to be done to develop meaningful and reliable evaluation procedures (in vivo) and couple these with physical and chemical parameters (in vitro) which adequately characterize the material. The coordinating government agency lacks the capacity for imposing scientific standards of measurement upon its materials research contractors, and fundamental life-science questions such as the clotting mechanism of blood go unanswered as empirical solutions to nonthrombogenic surfaces are sought. A further obstacle is that the basic research work must be done in an atmosphere where materials research is integrated with device development and medical and surgical use; such work should be carried out at university-medical school complexes. This is being recognized and preliminary (NSF) funding is encouraging these types of interdisciplinary studies. On the other hand, as long as the delivery of medical services holds major attention, it will be difficult to establish sufficient priority for questions in the biomedical materials area.

Nonetheless, there is much activity in some of these fields. For example, the search for nonthrombogenic vascular-substitute materials had led to the screening of a large number of commonly available as well as new materials prepared specifically for this use. At present, the most promising candidates range from simple materials, hydrogel, carbon, and copolyetherurethanes to albuminated surfaces, fibril (both cell-seeded and non-cell-seeded surfaces on silicone rubber) and copolyetherurethanes. However, the knowledge of why these materials work is still largely speculation. Also, variations in fabrication techniques, identification techniques, surgical-implant techniques, etc. all can influence the final results.

In other areas, fiber-reinforced plastics are being evaluated as an orthopedic substitute. A variety of membrane-fabrication techniques are being employed to produce improved performance of economically attractive oxygenator systems. For the most part, however, these membranes are common materials cast or spun into membrane configurations.

Because of the fragmented nature of the industry supplying biomaterials it is difficult to gain an overview. Table 4.22 attempts to do so by linking specific materials with the impact that each has on its general characteristics and on health care specifically.

Additional Note on Materials Research Problems

Foreign (including man-made) materials have been used in the repair of diseased and ravaged tissues for many years. These uses have ranged from temporary assist materials, to long-term (essentially permanent) hard- and soft-tissue replacements. In almost every case, the material used was developed for commercial purposes far removed from the biomedical environment. As a result, while there has been a tremendous advance in some areas, there have also been failures.

Two areas where much data are available to judge the MSE approach (or lack of it) are in orthopedic and in cardiovascular surgery. These are briefly discussed below.

Table 4.22 Materials Innovation in Health Care

Material	General Impact	Health Care Impact
Tungsten	refractory metal	x-ray targets
Stainless Steel 316	corrosion resistant	orthopedic
Vitallium	high strength	
Titanium	metals	prostheses
Pyrolite (pyrolytic carbon)	reactor moderator	nonthrombogenic surfaces
LaOBr: CsI-phosphor	x-ray scintillator	x-ray phosphor
(SbNaKCs) —photoemitter	photoemitter	x-ray image intensifier
Epoxy	adhesives	dental prostheses
Acrylic	plastic	dental prostheses
Nylon	synthetic fabric	surgical—orthopedic prostheses
Dacron	synthetic fabric	surgical prostheses
Silicones	rubber substitute	surgical prostheses membranes, disposables
Silicon	transistors	instrumentation implanted electronics
PVC	plastic	throw away items
PPO-copolymer	synthetic	oxygenator membranes
Polyethylene and polypropylene	plastic	orthopedic prostheses
Copolyetherurethanes	spandex elastomer	vascular grafts
Cellulose fibers	natural polymer	artifical kidney membrane

Materials in Orthopedic Surgery

Metals have been used for orthopedic applications for over 400 years. The primary function of orthopedic prostheses is for the internal fixation of fractures—screws, pins, plates, and nails. One of the classical rules for optimum fracture repair is immobilization. If this cannot be achieved by external splinting, the orthopedist must often surgically enter the fracture region and directly splint and fix the bone. The fixation device may be removed after healing is completed or it may be left in place indefinitely— depending on the age of the patient, the patient's opinion, and the surgeon. Practically every available pure metal and a variety of alloys have been implanted for a variety of applications. Much of this work has been largely empirical. The great majority of the materials tried have not been successful because of inadequate mechanical properties and/or poor corrosion resistance. However, corrosion is not a major problem with today's surgical alloys. There is still some concern, however, about faulty design and inadequate quality control of these devices, but in general most are quite satisfactory and do an adequate job.

One of the most challenging and difficult areas of modern orthopedic surgery is the surgical management of defects of synovial joints, largely in elderly and rheumatoid patients. The hip joint has received the most attention, although work is in progress on the knee, finger, and elbow joints.

A variety of devices and techniques exist whereby fractures of the head of the femur may be corrected. If the joint region itself is malfunctioning, but the bone is healthy, the joint can often be regenerated by a method known as cup arthroplasty. In many cases, however, one or both joint surfaces are deteriorated beyond repair. The only solution at present appears to be total joint replacement with a prosthesis. A commercial artifical hip joint consists of a ball attached to a long stem, which is friction fixed into the medullary canal of the femur. The mating surface (artificial acetabulum) is attached to the pelvic bone. The problems are many.

Fixation of the implant to the skeletal system is almost almost always inadequate, particularly on a long-term basis. The adhesion is a mechanical locking. Rarely is there ever any true adhesion across the implant/bone interface. Porous surfaces are being evaluated which permit bone ingrowth and hopefully a more stable fixation. Wear and lubrication in these joints is a major problem. Wear debris is common in the vicinity of such joints, often producing a substantial tissue reaction. Excessive wear and inadequate fixation eventually produces a malfunctioning joint, often one which literally wobbles

The artificial hip is a success in terms of relieving pain, restoring function, and general patient rehabilitation. Unfortunately, the success is not a long-term one. Usually complications develop after a number of years which greatly compromise the function.

Materials in Cardiovascular Surgery

The next largest use of implantable prostheses is in cardiovascular surgery, as in synthetic arteries and heart valves. Perhaps the most difficult problem with the use of materials in contact with blood is the tendency for blood to clot when exposed to such materials. Though a number of mechanisms have been postulated, very little is known about blood/surface interactions. Also, relatively little basic work has been done on protein adsorption, cell adhesion, etc., i.e. the factors that initiate these adverse reactions.

In early studies on the repair of damaged vessels, solid impermeable tubes for blood conduits were employed. The poor results led surgeons to use transplanted vessels. They observed that transplanted vessels slowly die and disappear, leaving a skeleton which acts as a scaffold for new tissue growth. The new tissue growth forms a natural vessel-like lining in the inside of the tube which minimizes thrombus formation. Thus, vascular surgeons began studying how to develop this biological porosity, i.e. by the use of weaves, knits, velours, felts, etc., as porous blood conduits. These showed a high degree of success with limitations in terms of effective size. Relatively large diameter arteries (6–8 diameter and larger) were satisfactory, while smaller ones were not. Also, venous grafts gave trouble.

The success of the porous grafts depended on a series of responses: (a) the graft is preclotted and the interstices filled with clot (fibrin); (b) the graft is implanted—the clot surface is in contact with blood, and the outer clotted surface is in contact with the surrounding tissue; (c) during the first few weeks after implantation, connective tissue penetrates into the pores and begins to digest and organize the clot on both sides of the graft (this is to be expected—any typical wound-healing response consists of connective tissue cells penetrating into the clot, removing it, and restoring wound continuity; (d) the organization of inner surface is followed by blood vessels penetrating the graft through the pores; (e) as the inner surface becomes organized, it begins to mature and remodel, resulting in contraction (again, a classical wound-healing response). The contraction may result in pinching off the blood vessels, shutting off the blood supply, and resulting in tissue death. This does not occur if the fabric is of fairly high porosity; (f) thrombosis or calcification may occur at this stage, or the dead and dying tissues may incite a second wound-healing response. Also, the lining may sluff off, forming an embolus.

This process usually works well, though occasionally the inner layer may continue to grow, resulting in decreased flow or even stoppage. The situation gets more critical as the vessel diameter decreases. The very high porosities necessary to allow a viable inner lining means that there is a great risk of hemorrhage during the several weeks that the lining is forming. Also, the fixation of the artificial vessel to the natural vessel is not good. As a result, the strength of the juncture is dependent on the suture.

The development of successful vascular grafts has required controlled porosities and anti-kink properties as well as the creation of new fabrication processes to produce seamless bifurcations. It also required the cooperation of vascular surgeons, textile engineers, and experts on wound healing and blood clotting.

Present research is centered on compound vascular grafts, i.e., grafts containing a slowly dissolvable component which initially plugs the pores. The result is a graft of low initial porosity, but very high biological porosity. Again, these approaches suffer from a lack of fundamental knowledge of why blood acts as it does; therefore, an empirical engineering design approach is used.

Both of the above areas are presently materials-limited. Further development must be coupled with understanding of the materials function in the environment at play.

Other Materials-Limited Areas

There are many examples wherein materials constraints have greatly slowed or even stopped the development of an acceptable medical technique. The artificial kidney is an excellent example.

The laboratory procedure of dialysis (mass transport thrugh a semi-permeable membrane) was extended in 1913 to the perification of the blood of animals. While these efforts were successful in showing that hemodialysis was possible, the lack of reproducible membranes and anticoagulents kept this from developing into anything more than a laboratory experiment. It was not until thirty years later when, because of the developments outside the field of medicine resulting in the availability of both the anticoagulent heparin and a relatively inexpensive, reproducible cellulose membrane material (i.e., cellophane), that we saw hemodialysis move from the laboratory to the clinic. In 1943, Dr. Willem Kolff reported the development of a rotating drum type of “artificial kidney” and its successful use on a patient with acute kidney failure.

During the next two decades, there were many engineering and medical refinements leading to two major types of devices—the twin-coil and the flat-plate artificial kidneys. However, in all these years the artificial kidney was used primarily for patients with acute kidney failure in which restoration of renal function was anticipated. This restriction was primarily based on the lack of a good method for coupling the patient to the artificial kidney device. The shortage of suitable radial arteries and veins, and their subsequent loss of accessibility after the surgical procedure needed for dialysis, meant that only a limited number of dialyses could be performed. The longest patient survival using intermittent dialysis was 181 days.

In the late 1940’s, an indwelling vascular cannulae bypass shunt was studied as a technique to provide easy access to the patient’s blood system. However, only glass and rubber tubings were available for constructing the bypass device and these clotted severely unless the patient was continuously heparinized. It was not until 1960, when again developments outside the medical field in materials (i.e., the commercial availability of polytetrafluoroethylene-teflon, and polydimethylsiloxane-silastic rubber) enabled the development of practical indwelling cannulae for prolonged hemocialysis. With this development began the era of prolonged chronic dialysis. From the original patient (who is still alive), we have seen the procedure expand until today there are approximately 3,000 patients in the U.S. on chronic dialysis.

Improved engineering of devices has led to less expensive equipment, overnight unattended dialysis in the home, etc., and has made hemodialysis available to more people. (In the U.S. approximately 55,000 patients a year die of renal causes. On the basis of current medical selection criteria, it is estimated that 7,500 patients per year in the U.S. alone are suitable candidates for chronic dialysis.)

However, even with these accomplishments during the last decade, we are again on a plateau where new materials for both membranes and the cannulae and blood circuits are needed.

The current materials—cellulose membranes, polytetrafluoreothylene, and polydimethylsiloxand—are not ideal in their properties. For example, the membrane material is essentially the same as that used by Kolff in the 1940's. While many lives have been saved, recent reports indicate not only a disturbing trend in less full rehabilitation of the surviving patients, but an increase in patient complications. Many nephrologists believe the insufficient removal of medium and large size molecules may be responsible for the development of secondary complications. New membranes, specifically designed to allow the efficient removal of toxic materials from the blood are truly needed. Also, if these membranes could have a blood-compatible surface, problems relating to clotting could be reduced.

There are also many problems with the cannulae bypass system. The average of eight-month survival per site is not good, with problems such as clotting, mechanical trauma of the vessel wall, and infection still occurring with too high a frequency and causing failure. Much of the failure can be directly attributed to the lack of an ideal polymer that is compatible with both blood and tissues. Again, we are essentially using the same types of materials adopted by Scribner and Quinton in their original cannulas.

Therefore, new materials are necessary for membranes and cannulas. We can hardly afford the luxury of waiting for needed materials to fall out from future industrial processes slanted for commercial goods, but should seek these biomedical materials in their own right. To do this requires the development of much basic knowledge in the diffusional and surface properties of polymers.

Artificial hearts, heart-assist devices, and artificial heart valves are additional examples where limitation of the biomaterial state-of-the-art severely restricts further advances. Again the problem is largely one of blood compatibility. Post-operative complications of artifical heart valves and heart-assist devices are largely attributable to clot generation (emboli). It is generally recognized that materials constitute one of the major constraints delaying the artificial heart.

It is only within the last few years that the medical and materials communities have earnestly sought materials specifically produced or modified for medical applications, rather than relying on available materials developed for entirely different applications. The development of water-swellable, soft hydphilic gel known as Hydron was the result of a long discussion between polymer chemists and surgeons. The production of a truly pure, medically acceptable silicone rubber was the result of an industrial firm (Dow Corning) responding to a medical need. Examples such as these are still the exception.

There has been considerable progress in developing medical implants which has required the solution of difficult corrosion problems, tissue reactions, and the modification of surgical procedures. Further work is needed, of course; for example, in the problem of fixation of implants to bone and bioadhesions.

Fundamental bone-foreign surface studies are not at hand. The basic mechanisms of lubrication and fixation of natural synovial joints are not well known. Substantial design input from biomechanicists is needed. It is clear that in the past implants have been designed by inventive and creative surgeons, often with little understanding of mechanics. This is changing. The surgeon, biomechanician, and biomaterials specialists are beginning to work together.

An exciting area of orthopedic biomaterials research is that of bone ingrowth into porous metals and ceramics. It has been demonstrated that bone will grow into 100 micron diameter pores or larger for relatively large distances. There is hope that implants containing the appropriate surface porosity can be firmly and stably fixed to bone by such a mechanism. This research is requiring the expertise of the ceramist, powder metallurgist, orthopedist, and biomechanician, as well as the bone specialist.

Another area of importance is the study of blood and its relation to foreign materials. One of the key problems in implant materials today is the lack of true blood compatibility. Practically all nonliving materials (and many living structures as well) induce blood-cell damage, clot formation, and protein destruction. Various surface properties have been studied, including charge, surface free energy, hydrophilicity, roughness, and surface stress, but little or no correlations are certain. Surfaces containing bonded heparin (an anticoagulant) and aqueous gel surfaces show a degree of blood compatibility, as do some negatively charged surfaces but the results are yet to be proven clinically. The major problem is the complexity of blood, and the general lack of knowledge of interfacial reactions of blood. This is clearly an area where the interdisciplinary philosophy of MSE can have a major impact.

Yet another prospect is that of biologically active implants. Typical surgical implants, such as bone plates, sutures, shunts, etc., perform physical and mechanical functions, but generally exhibit no chemical activity. A new direction in implant engineering is that of implants with biochemical activity—implants which will actively participate in local biochemical processes. Such an implant must be biocompatible (no adverse reactions can be tolerated) and yet be bioactive.

A bioactive coating or surface is one which can actively enter into biochemical reactions with living organisms or with compounds derived from living organisms. This activity can range from biocidal—the actual killing of living things—to delicate, specific enzyme-catalyzed biochemical reactions

Summary and Outlook

Health care is primarily a service industry, dominated by practicing professionals, in which materials other than pharmaceuticals play a generally subordinate role. Recently, however, several well-publicized advances in surgical techniques have employed selected materials which had earlier been developed for nonmedical purposes. Although attempts are now being made to develop special biomedical materials, this effort is hampered by the failure of the biomedical-materials field to define quantitative goal specifications and standard materials-characterization procedures. Biomaterials research in industry is hard to justify in view of the small volume of materials consumption, and federal agencies appear unable to impose industrial MSE procedures on contract and grant recipients. This is so mainly because there is a lack of fundamental knowledge of the interactions between living and nonliving systems, and so there is severe difficulty in achieving whatever specifications one might set. What is needed, in other words, is a foundation on which to build.

The highest national health priority is currently assigned to the improvement of general health care services. Health research, particularly in those surgical areas which call upon special medical materials, has a relatively lower priority now than it did several years ago. This shifting national goal foreshadows changing markets for medical-service equipment, and it is in this direction that materials advances are now most likely to contribute significantly to general well-being.

The contributions which can be made by MSE to improved health care are clearly important. Significant progress, however, will require departure from two well-established traditions. First, biomaterials research requires a close working relationship between medical and materials professionals on an equal footing. This will depend on a broadened perspective among some of the medical community who have felt that only MD’s can contribute to health problems. Likewise, the biomaterials expert must interact with a wide variety of disciplines which are far removed from “classical” MSE, including all of the various surgical subspecialties, as well as biochemistry, hematology, immunology, urology, cardiology, orthopedics, microbiology, pathology, histology, physiology, and pediatrics. The interaction must be much more than a mere shaking of hands, but must involve understanding—which means studying and learning these many disciplines as they are needed, at least on an introductory level.

Secondly, the problems in this field are so complex, with so many specialized facets, that a sizeable team is required to make significant progress, perhaps at an annual rate on the order of $1,000,000 for each additional program. This is quite a departure from the tradition of supporting academic research in units of one faculty member, and will necessitate considerable adjustment both on the part of the funding agency and by the university administrative structure.

ENVIRONMENTAL QUALITY AND MATERIALS NEEDS

Background

Concern for environment has been a recent but rapidly-rising national goal. To be sure, it has its historical roots, some reaching back many decades. Believers in the tenets of what has been called the American Conservation Movement, early in the 20th century, and even before that, men like George P.Marsh were troubled over man’s relationship to nature. But the concern that gathered momentum in the 1960’s hit with such force that, within the short span of a decade, a great variety of laws and institutions has

has arisen together with well-articulated popular aspirations, which have spun a whole new web of tasks all subsumed under the heading of “environmental quality.”

In concentrating on the 1960’s as the era of this new concern, one may come in for some criticism. The Refuse Act of 1899, for example, made it unlawful to discharge or cause to be discharged, into the nation’s navigable water, or tributaries thereof, “any refuse matter of any kind…other than that flowing from streets and sewers…” But while the Act was on the statute books and its provisions subject to enforcement by the Corps of Engineers, the nation’s rivers, lakes and estuaries became dirtier and dirtier. The rediscovery in 1970 of this Act as a suitable tool for water-pollution control can be understood only in terms of the prominence that “clean rivers” had assumed by then, just as its previous disregard merely reflected the absence of a pressing problem or felt need. Similarly, many cities have had ordinances dealing with dirty air as a nuisance, and monitoring of air began on a substantial scale in the early 1950’s. But a national attack on the causes of pollution did not materialize until the sixties.

The early moves were small-scale efforts. First Congressional attempts to pass a water-pollution control bill in 1936 and 1938 failed altogether; nor did legislation emerge from the strong warnings contained in a 1939 report by a Special Advisory Committee on Water Pollution of the National Resources Committee, which pointed to the role of water not only as a public health matter, but to its recreation role as well as its importance for fish and wild-life. It was not until 1948 that a Water Pollution Control Act was finally put on the statute books. As passed, it was temporary, experimental, and its financial provisions comprised only $5 million in expenditures and $22.5 million in landing authority. Even so, after five years, none of the lending authority has been used.

It was the 1948 Act, nonetheless, that became the base for later legislation, culminating in 1965 in passage of the Water Quality Act. Appropriations and lending authority rose sharply to the multi-billion dollar level, and administration was transferred first from HEW to the Department of the Interior (signifying the recognition that more than health was involved) and in 1970 to the newly established Environmental Protection Agency, based on the judgment that (a) environmental concern with different media needed an integrated approach, and (b) such concern should be carefully divorced from agencies that have missions in resource development.

The general point to be made is that while scattered legislation and administrative provisions pertaining to environmental matters existed prior to the 1960’s, escalation of concern and action in the past decade has been such that the sixties can be legitimately tagged as the era in which environmental enhancement first assumed the characteristics of a national goal. In addition to the Water Quality Act of 1965, pertinent legislation in the air-pollution field are the Clean Air Act of 1963, the Air Quality Act of 1967, and subsequent amendments. In the matter of solid waste, the Solid Waste Disposal Act of 1965 and its amendment by the Resource Recovery Act of 1969 fulfilled similar functions. A keystone law, the National Environmental Policy Act of 1969 (NEPA), signed into law on January 1st, 1970, coupled with the establishment of the Environmental Protection Agency toward the end of 1970, set up much of the machinery that now guides and implements federal policy. The environmental impact statement, required under Sec. 102(C) of NEPA, has become a major vehicle for the evaluation of environmental policy and its application, and the courts are now broadly involved in helping to determine the boundaries of environmental concern and action. Presidential messages on the subject have accelerated from what in retrospect appears a modest beginning in President Johnson's "Protecting our Natural Heritage" message of January 1967 to major and complex messages by President Nixon in 1970, 1971, and 1972, calling for expenditures of many billions of dollars annually. Table 4.23 provides a brief summary of major objectives as culled from Presidential Messages from 1967 to 1972.

Given the recency of the environmental goal, we had best refrain from trying to establish trends in any detail. Suffice it to say that, in general, one may spot a slight shift from attempts to clean-up towards attempts to prevent; and from concentration on technological remedies toward economic incentives and institutional remedies. But technological remedies remain a major plank, together with economic, social and political approaches.

Materials tasks can be derived from environment-associated issues in the following types of situations, some of which are illustrated in the balance of this section:

Effluent abatement

(a) process restructuring
(b) containment
(c) recycling

Materials substitution

(a) through alteration of existing devices
(b) through substitute devices

Functional substitution
Waste disposal

(a) increased degradability
(b) reduction in noxiousness

Increased recyclability

(a) through design
(b) through suitable materials choice

A few general remarks before we come to details. Since most of what we call "the pollution problem" is generated by the displacement, processing, use, and disposal of materials, whether these be of organic or inorganic, natural or man-made origin, it is at once obvious that materials research occupies a central position in environmental management. Ideally, the flow of materials ought to be so structured that the residuals can be swept up in the on-going stream of natural geological, hydrological, meteorological, and biological processes without causing modification of the air, land, or water in ways harmful to living things generally, and to life-supporting natural systems. In fact, this ideal will not be achieved until we have improved

Table 4.23 Environmental Goals as Presented in Presidential Messages, 1967–1972

January 30, 1967

AIR POLLUTION

Set emission controls for industries that contribute heavily to air pollution.
Establish Regional Air Quality Commissions to enforce pollution-control measures in “regional airsheds.”
Provide Federal assistance in establishment of state system for regular inspection of vehicle pollution control devices.
Improve enforcement procedures.
Accelerate research in fuel additives.
Intensify and broaden efforts to understand and control air pollution, with research targets to include:

motor vehicle emissions.
smoke and odors from diesel engines.
SO_2 emissions.
low-sulfur or sulfur-free fuels.

RESOURCE DEVELOPMENT

Develop geothermal power.
Increase knowledge of ocean resources.
Develop rapid excavation techniques.
Examine nonfuel mineral needs.
Strengthen capacity to cope with energy policy issues.

WATER QUALITY

Review and approve state water quality standards.
Encourage river basin plans for pollution control.
Support work on advanced treatment methods to allow water re-use at reasonable cost.

Explore means to encourage industry and local governments to abate water pollution.

OTHER AREAS OF CONCERN

Parks.
Wilderness areas.
Scenic rivers and trails.
Recreation areas.

February 10, 1970

AIR POLLUTION

More stringent motor vehicle emissions standards.
Revision of enforcement procedures.
Authorize HEW to regulate gasoline composition and additives.
Initiate R&D programs to produce unconventional, low-pollution automobile within 5 years.
Initiate testing and evaluation programs to assist private developers of unconventional automobiles.
Establish national air quality standards, with states preparing abatement enforcement plans.
Accelerate designation of interstate air-quality control regions.
Establish national emissions standards for extremely hazardous pollutants.
Provide fines for violators of standards.

WATER POLLUTION

Extend federal-state water quality program to all navigable waters and their tributaries, groundwater, etc.
Several measures to help finance municipal waste treatment plans

Treatment plants to be built to prescribed design, operation, and maintenance standards and to be operated by certified operators.
Impose fees on industrial uses of municipal treatment plans to meet treatment costs.
Establish comprehensive river basin plans.
Encourage large-scale, regional treatment facilities.
Establish precise effluent standards for all industrial and municipal sources.
Facilitate initiation of court action against violation and enforcement procedures generally, injunctions, fines, etc.
Water-quality controls on concentrated animal feedlots.

SOLID WASTE MANAGEMENT

Redirect research to recycling and easily degradable materials.
Develop incentive systems for prompt scrapping and recycling of automobiles and recycling generally.

OTHER

Parks and recreation matters.
Phase out DDT and other pesticides.

February 8, 1971

AIR POLLUTION

Develop a clean-air emissions charge on SO_2 emissions.
Establish special tax on leaded gasoline.

WATER POLLUTION

Repeats need to provide funds and financing measures and improve methods generally to assist in construction of treatment plants, and to extend program to all navigable waters, etc.

Establish Federal standards to regulate discharge of hazardous substances into water.
Require use of best practicable technology in new industrial establishments.
Repeats and amplifies need for more effective and rapid enforcement procedures, etc.
Empower Administrator of EPA to require reports by anyone responsible for discharging effluents covered by standards.
Develop better means of preventing and cleaning up oil spills.

SOLID WASTE MANAGEMENT

Have Federal government revise its specifications to encourage use of recycled paper. Encourage states to do likewise.

TOXIC SUBSTANCES (N.B.—Heading appears for first time)

Empower Administrator of EPA to restrict use or distribution of substances hazardous to health or environment.
Improve enforcement procedures.
Prescribe minimum standard tests on substances.

OTHER

Establish registration procedures for pesticides, streamline cancellation procedures, set up controlled testing methods, and improve and tighten enforcement.
Regulate ocean dumping with view to phasing-out dumping of harmful materials, and develop initiatives for international control.
Develop means of noise abatement control.
Establish a national land-use policy, comprising management of public land, preserve natural environment, open spaces, wilderness areas, recreation areas generally, development of power-plant siting legislation, mined area protection in locations of underground and surface mining.

February 8, 1972
(Note that the conventional headings have now disappeared)

Toxic wastes - control disposal on and under land.
Sediments - control sediments from earth-moving activities that affect water quality.
SO_2 - establish charge on sulfur emissions into the air.
Energy - Develop new “clean energy” technologies.

Require better insulation in federally-insured structures.
Determine energy conservation measures.

Recycling - Determine availability of tax-exempt bond financing for private recycling facilities.
Noise - increase funds for research.
Pollution, general - increase funds for research on health effects, modelling, etc.
Land use - Require states to control siting of major transportation facilities.

Discourage unnecessary development of wetlands.

Other

Pesticides - Promote integrated forest management.
Predators - Bar use of poisons on public lands and favor state research along similar lines.
Endangered species, etc. - Look towards early action to prevent depletion and tighten enforcement; improve protection of migratory birds
Parks, etc. - Establish new parks, wilderness areas, control use of off-road vehicles.

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materials processing technologies for properly channeling the great flux of matter through the economy, and some improved materials of construction for use in the process, and until we have modified our institutions and incentives in ways that will lead to the adoption, functioning, and continuing improvement of such technologies.

The need is not, however, solely for new ways of transforming one material into another, or making different sorts of materials having desired sets of properties. Even more important are the needs for processes that carry out desired transformations more economically or with reduced generation of residuals, or pollution-control materials that are less expensive; or disposable materials that can be accepted into the biosphere after passage through conventional social channels. Development of technologies that permit environmentally compatible materials processing at reasonable costs, and environmentally harmless structural materials that are compatible with minimal change in social habits will greatly aid implementation of proposed environmental quality standards, and may even be crucial to their attainment.

Specific Areas of Concern

The challenges to MSE are particularly great in the areas of water pollution, air pollution, solid-waste management, and toxic substances.

Water Pollution

The widely quoted data presented in Table 4.24 indicates that the materials processing industries (all but the last four items in the table) produce about two-thirds of the total water pollution—created by non-agricultural human activities in the U.S. The average costs of meeting current effluent standards in these industries during 1974 are projected to run in the range 0.2–1.6 percent of sales, (Environmental Quality 1971, p. 123). This suggests that these industries as a whole can probably meet existing water-quality standards without much disruption. An increase in effluent quality from that provided by partial treatment, as above, to that given by complete treatment could easily increase the treatment costs 10-fold, even when a known technology exists to do the job (ibid., pp. 118–119). The level of cost increase in basic commodities that would ensue would almost certainly give rise to serious dislocations and controversy.

A more striking situation pertains to the processing of domestic sewage. This contributed only 30 percent of the tonnage of 1964 water pollutant discharges, but its treatment even to existing standardw will require two-thirds of the total treatment expenditures (Environmental Quality 1971, pp. 114–115). The added costs required to meet higher standards using existing technology will meet legislative resistance. New materials of construction to lower the costs of sewer-line and sewage-plant construction, new treatment techniques, new process controls to ensure effluent quality, and new process materials would relieve the pressure generated by the establishment of new goals.

Table 4.24 Estimated Volume of Industrial Wastes Before Treatment, 1964[1]

Industry	Wastewater volume (billion gallons)	Process water intake (billion gallons)	BOD (million pounds)	Suspended solids (million pounds)
Food and kindred products	690	260	4,300	6,600
Meat products	99	52	640	640
Dairy products	58	13	400	230
Canned and frozen food	87	51	1,200	600
Sugar refining	220	110	1,400	5,000
All other	220	43	670	110
Textile mill products	140	110	890	N.E.
Paper and allied products	1,900	1,300	5,900	3,000
Chemical and allied products	3,700	560	9,700	1,900
Petroleum and coal	1,300	88	500	460
Rubber and plastics	160	19	40	50
Primary metals	4,300	1,000	480	4,700
Blast furnaces & steel mills	3,600	870	160	4,300
All other	740	130	320	430
Machinery	150	23	60	50
Electrical machinery	91	28	70	20
Transportation equipment	240	58	120	N.E.
All other manufacturing	450	190	390	930
All manufacturing	13,100	3,700	22,000	18,000
For comparison: Sewered population of U.S.	[2]5,300		[3]7,300	[4]8,800

[1] Columns may not add due to rounding.

[2] 120,000,000 persons times 120 gallons times 365 days.

[3] 120,000,000 persons times 1/6 pound times 365 days.

[4] 120,000,000 persons times 0.2 pound times 365 days.

Source: Data derived from T.J.Powers, National Industrial Waste Assessment, 1967.

Air Pollution

The materials-processing industries make an appreciable contribution to our total air pollution, although a relatively less important one than in the case of water pollution. Similarly, the estimated control costs are generally quite modest (estimated at 0.1–0.5 percent of sales). The one big exception lies with primary metals production. Here, the estimated average cost to meet current standards is 2 percent of sales, and tighter standards on emissions of sulfur, fluorides, and heavy-metal dusts and vapors are widely anticipated. Improved technologies in extractive metallurgy and metals processing are obviously essential.

The major sources of air pollution are fossil-fuel-generated heat and power production (a challenging problem in materials-process engineering) and, above all, the ubiquitous internal combustion engine. Under current legislation, all vehicles from the 1975 model year on are to have control devices that will reduce emissions of carbon monoxide, hydrocarbons, and NO_x to very small fractions of their 1960-era levels. Where catalytic converters are used, the estimated costs range from $200 to $600 per automobile, and their estimated lifetimes are still quite uncertain. The materials aspects of this problem are crucial, and maintenance ranks as high as the original condition. Unless the costs and durabilities of the catalyst blocks, ceramics, and structural metals used in these converters can be sharply improved, the effort to control air pollution by this means could well come to naught.

Solid Wastes

The U.S. mines or imports 10 million tons of sulfur each year while blowing 13 million tons out into the atmosphere as air pollution, and mines or imports 1700 million tons of combustible organic matter (fossil fuels) while discarding 1100 million tons as solid wastes. In addition to combustible organic matter, municipal and industrial solid wastes contain millions of tons of glass, ferrous metals, recoverable paper fiber, and nonferrous metals. Recycling of these waste products will have to be greatly stepped up if we are to reduce the adverse impact of production and consumption on environment.

Means of overcoming critical barriers here are represented by a variety of better materials-processing technologies: for sifting out and drying refuse; for separating out the nonferrous metals and glass; and for converting clean organic refuse to compost or microbial protein or low-sulfur solid fuel. Improved structural materials could also have an impact: acid-resistant firebrick for incinerator construction; materials and designs for electrical conductors and other automotive accessories that will facilitate recycling the worn-out hulk; and self-destructing containers and packaging materials to reduce litter. In contemplating recycling technology, one must be careful though to keep in mind (a) that the recycling process itself tends to generate pollution problems so that there, too, a materials problem arises, and (b) that a process change rather than a proper disposal scheme must always be considered as an alternative.

Toxic Substances

The problem of developing nonpersistent pesticide materials is beyond the range of what is usually considered as MSE, at least for purposes of this report. But the materials problems posed by nuclear-reactor construction and radioactive fission-product confinement are pertinent; they have already been discussed in connection with power generation. There remain the problems arising from the dispersal into the environment of a variety of industrial products: solvent vapors, polychlorinated biphenyls (PCB), phosphates, and heavy metals. Each poses a separate set of tasks for the materials scientist or engineer: solventless surface coatings that can be cured by means other than simple drying; stable, nontoxic, noninflammable heat-transfer and dielectric fluids that are nonpersistent in the environment; household and industrial cleaning agents that are effective in hard water and yet still nonconducive to waterway eutrophication; substitutes for mercury and cadmium in disposable products; and effective effluent-control techniques for those industrial operations that must still use such toxic heavy metals in their processes.

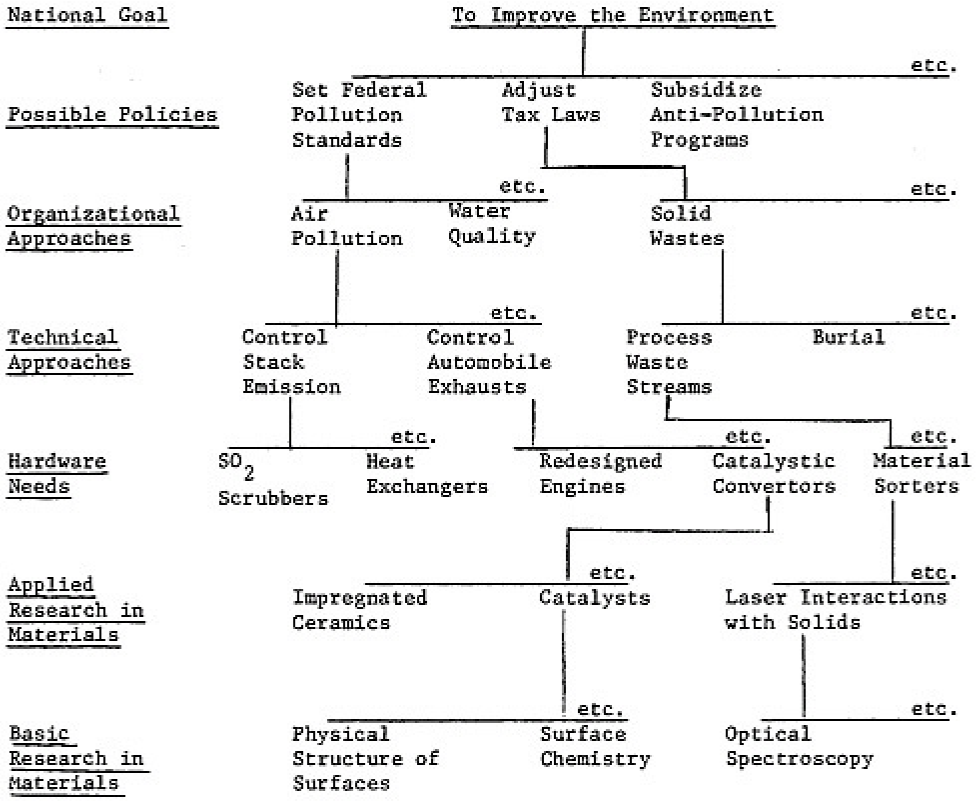
Figure 4.7 illustrates a partial relevance tree for relating materials research to environmental goals.

Additional Opportunities for Materials Science and Engineering in Environmental Control

Perhaps one of the most direct interactions between MSE and a societal goal occurs in environmental quality. Leaving aside pollution from agriculture, almost all pollution problems are caused by materials. Much pollution results from the generation of undesirable materials, for example, slag piles surrounding mines and factories, industrial waste flowing into streams, and large smoke stacks pouring pollution into the air. Another familiar example of material pollution is the automobile hulk which can be seen rusting in junkyards across the country. Many pollutants could be reduced or eliminated by suitable effort in MSE. An urgent problem is the emission of noxious gases by automobiles. A suitable catalyst which is economically feasible might control this problem. Industrial effluents which are by-products of manufacturing processes can be recovered in many cases by suitable reactors, precipitators, or scrubbers. The highly undesirable sulfur dioxide released in the burning of most coal needs to be chemically reacted in a suitable bed before the exhaust gases are released to the air. In sum, it can safely be said that materials pervade the pollution problem.

Much of the pollution problem which is now receiving public attention has resulted from inadequate attention to all portions of the materials cycle. Up until recently, the materials designers and manufacturers have tried to optimize their particular program starting from the source of the material and carrying on up to the product or service which is marketed. Little attention has been paid to the remaining problems in the cycle, i.e., the generation and management of secondary effects, and the disposal or

Figure 4.7 Partial Relevance Tree for Environmental Goals



reclamation of junk and waste. With increasing population density, with rising affluence and with the expanded utilization and complexity of technology, we now recognize in a more complete way the critical importance of these stages of the material cycle to our well-being. From now on, every individual involved in the processing of materials will need to optimize his contribution in the framework of the entire materials cycle starting from recovery of primary raw materials and concluding with waste disposal or reclamation. The proper cost allocation of this new approach is a most difficult question, but the technical impact on the materials man is quite clear. He must now select or design a material not only for its immediate application and primary function, but for the management of all flows including final disposal of the used-up product. A major share of the improvement in environmental quality will be contributed by the MSE community. Their actual technical contributions will have to be closely integrated with new regulations, consumer preferences, design, quality control, economics, and production techniques. The more complete understanding of the relations between composition, structure, and the use properties which MSE provides is the most effective tool for responding satisfactorily to the many demands which are being placed on materials.

There are several approaches by which MSE can contribute to a better environment. New processes can be developed which reduce or eliminate the generation of undesirable waste or by-products. For example, in the fabrication of printed circuit boards for electronic circuits, present processes start with a substrate completely covered by a copper film. A sequence of chemical etching steps removes the unwanted copper, leaving the desired circuit paths. The etched copper must either be reprocessed or appear as waste effluent. Soluble copper wastes in excess of five million pounds per year are being created by the printed circuit board industry. New processes have been developed which start with an unclad board and deposit copper from a chemical bath only on those areas where conductor patterns are desired. This can be accomplished by a specialized ink which is printed on the unclad board or by a photochemical coating which can be optically activated and chemically developed to yield complex copper interconnection patterns. Either process yields the dual advantage or avoiding undesirable waste and of reducing the cost of raw materials.

Another example of the importance of control of by-products is in the production of paper. The manufacture of paper now ranks second in the utilization of the forest resource in the U.S., out-ranked only by lumber. Paper is not only the hallmark of a literate society, but in the context of engineering materials it provides important elements for composites, such as honeycomb for low-density cores, and impregnating sheets for high-density plastic overlays (e.g., formica). Chemical processes for reducing wood to its basic fibrous elements involve dissolving the lignin cementing material which bonds the fibers to each other. The lignin, together with the soluble hemicelluloses and extractives, aggregate to about 55% of the total wood substance, all of which must be discarded or burned. Since disposal of this organic material, roughly 25,000,000 tons per year, results in adverse environmental effects, it is evident that improvement in processing methods is desirable.

Ideally, new processes should enhance the possibility of utilizing the organic constituents in the pulp effluent for useful purposes. A particularly attractive possibility is the reuse of the lignin fraction as a bonding agent for other wood materials, thus duplicating its original natural function. Considering the magnitude of the pulp and paper industry, any breakthrough in this regard would represent a major contribution to conservation of resources and to environmental improvement. This problem has proved to be particularly obstinate in the past despite concerted attacks by many qualified scientists throughout the world. New hopes ride on the application of sophisticated analytical techniques to uncover fresh leads to the chemical structure of lignin as it exists within and around the cellulosic lattice. Most studies to date have had to deal with lignin after having undergone severe chemical treatments to remove it from its functional location in the cell wall structure. High-voltage electron microscopy may prove useful in such studies of lignin in situ; in addition, radioisotope and laser technology may provide meaningful approaches to these problems. Finally, it should be mentioned that once the chemical and biological relationships are understood, it may be possible to combine genetics and forest-growth practices to provide a crucial modification in lignin structure so that the problems of pulping may become more tractable.

Materials science and engineering can lead to materials that are more amenable to economic recycling as well as to suitable application in a product or service. An everyday example is the glue which is used on some cardboard boxes. This glue gums up the paper-processing step so that such cardboard boxes are unsatisfactory for recycling further into paper products. A more penetrating study of the precise way in which glue effects a bond in terms of its composition and structure might lead to a material which is compatible with reprocessing. In the metals field, some alloying elements degrade the major metal constituent so that its recovery is economically unfeasible. Innovative materials designs should create alternative material systems which satisfy the design function at competitive cost, but also enable economic material recovery.

The processing of waste materials to recover useful products is another area in which MSE can make a significant contribution. An example that has already been shown is the manufacture of bricks from fly ash or coal-ash slag through the addition of suitable binders. A different way of making bricks has been developed where virtually any solid inorganic can supply the aggregate which, combined with a small amount of portland cement and a chemical accelerator, is molded under high pressure. Not only does this process make use of waste materials, but it provides a brick with properties which allow for new construction techniques with lower labor costs.

The development of cleaners, scrubbers, or purifiers can go a long way to avoid injecting undesirable pollutants into the atmosphere, streams, and lakes. One of the most needed contributions from MSE is a suitable catalyst to remove noxious gases from automobile exhuasts. Since our fundamental understanding of catalysts is in an early stage, considerable scientific progress will be required. The greatest success to date has been with catalysts based on platinum, but usage in every car may require so much material that the metal price will be increased substantially. A dual advance is, therefore, needed in this area from MSE; namely, an effective catalyst and one which does not use substantial amounts of platinum.

Materials science and engineering can also make a contribution by developing materials which are self-destructing after their useful life. The example which comes immediately to mind is the ubiquitous beer can which regretably litters so much of our landscape. For good economic reasons, the industry has turned to aluminum cans which, unfortunately, have almost indefinite life. How much better it would be to have a container which would blend back in with the environment with no undesirable side effects. This is a worthy challenge as an alternative to collection and recycling schemes.

In some cases, the most significant contribution can be made by developing materials which provide for longer service life, thereby reducing the rate at which junk is produced.

Existing manufacturing processes can be improved with regard to efficiency. Pollution is a problem of quantity; therefore, significant help can be given by incremental changes as well as by the more dramatic substitution of a pollution-free process for an offending one. Where long established manufacturing processes are attacked in depth for pollution reasons, it is likely that the new detailed understanding developed will also contribute to improved productivity, an important goal in itself.

Finally, it is important to point out that MSE can develop instrumentation for the more precise measurement of pollution both at its source and in its distribution. Examples are the tagging of oil so that leakage can be traced back to its source, and the collection of pollutant samples in water by surface reactions.

HOUSING GOALS AND MATERIALS NEEDS

The Federal Role—A Broad Summary

In the purchase of most homes, mortgage credit plays a crucial part, enabling the buyer to undertake the purchase and at the same time giving the mortgagor a role in determining the standards of value, durability, resale value, economic life, etc., of the home. Since the 1930's the federal government has become an increasingly active participant in this process primarily by (a) guaranteeing mortgages of reduced equity, (b) by assuring readily available mortgage funds, and (c) by regulating interest rates through the Federal Reserve System. Thus, federal standards and broader federal goals have become factors in the nature and the rate of home construction at various times. The government's influence has now extended to rental unit construction, originally for low income families and more recently as part of a national urban-renewal process. The instruments have been block grants to cities, appropriations to Municipal Housing Authorities, and subsidized mortgage insurance programs. In each case, standards of construction and various conditions of mortgage guarantee are specified.

As the major ultimate source of home-building mortgage credit, the federal government has thus been in a position not only to stimulate the housing industry as a specific component of the economy but also to influence the characteristics of the homes constructed. Because of its importance in the economy, national housing policy is cast as much with an eye to the general state of the economy as in purely social terms, i.e., providing adequate, low-cost shelter. Indeed, a review of congressional and executive actions during the late 1960's reveals increased emphasis on housing as an important segment of the economy as opposed to the social objectives of earlier housing legislation.

Recently the federal government has become involved in home ownership and operation. Where private builders have constructed low-income housing using federally-insured mortgage funding, and these mortgages have defaulted, the properties have reverted to the guarantor, namely the Secretary of HUD. But this has been an involuntary role. Indeed, when in 1968 Congress assumed a federal responsibility for the construction and rehabilitation of 26 million housing units during the following decade, Congress intended that this responsibility be discharged not through direct government involvement as a landlord but through the complex array of construction stimulants developed in the past four decades. To stimulate the construction of housing while keeping costs down has more recently led to attempts at controlling construction wages and to modest support of an industrialized approach to housing construction.

Changing National Housing Goals

Over the years, the emphasis in housing and urban-development legislation has changed from measures to provide mortgage credit for financing home ownership to the concern about the quality of the urban environment and the redevelopment problems of the nation's cities (see Table 4.25 for a detailed timetable of major events). The first really significant housing legislation was passed in the early 1930's when the Federal Home Loan Bank System, the Federal Housing Administration, and the Federal National Mortgage Association were established—agencies whose principal function was the stimulation of mortgage credit for homes and apartments of primary benefit to middle-income families. Slum clearance first emerged as a goal in the Housing Act of 1937 which established the Public Housing Administration. Interest in clearing slums, however, was secondary to shelter for the poor. Not until passage of the Housing Act of 1949 were slum clearance and redevelopment specifically authorized, in terms that set the stage for all of the housing legislation which has followed: "Congress hereby declares the general welfare and security of the Nation and the health and living standards of its people require the realization as soon as feasible of the goal of a decent home and a suitable living environment for every American family."

Federal government involvement in urban redevelopment has expanded greatly in the last two decades. Specifically, the Housing Act of 1954 turned the 1949 slum clearance and redevelopment program into an urban renewal

Table 4.25 Changing National Objectives and Priorities - Key Documents

A. Legislation

Date	Acts	Housing - R&D Aspects
1934	National Housing Act	- Home Mortgage Insurance FHA . middle class . economic stimulus
1937	U.S. Housing Act	- Low Rent Public Housing . shelter for poor . construction grants to cities
1948	Housing Act	- Prefab. Home Industry . housing R&D (301)
1949	Housing Act	- Slum Clearance, Urban Renewal . grants to cities . national housing goal
1954	Housing Act	- Urban Renewal . residential improvement mortgages . planning grants to cities
1955	Housing Act	- Mobile Home Courts . mortgage insurance
1956	Housing Act	- Housing R&D Authorized (602)
1961	National Housing Act	- Subsidized Mortgage Insurance - Low Income . mortgage payment assistance (235) . for apt. construction (221d3) . rental assistance (236) - Unsubsidized Mortgage Insurance . experimental home const. (233)
1966	Demonstration Cities Act	- Urban Renewal . housing R&D directed (1010) . $15M authorized
1968	HUD Act	- Housing Goal Reaffirmed (1601) . technology for low income housing (108) . technology for public housing (901)

Date	Acts	Housing - R&D Aspects
1969	HUD Act	- Mortgage Insurance for Mobile Homes Authorized
1970	HUD Act	- Research and Technology Program (502b) . $45M authorized (PL-92-78)
1970	Veterans' Housing Act	- First VA Mortgages for Mobile Homes
1971	S1859	- National Institute of Bldg. Science

B. Other Documents

1967-68	Report, Commission on National Urban Problems - comprehensive, social, need for housing
1968	Report, President's Committee on Urban Housing - technical, needs, costs
1969	Report, Cabinet Committee on Price Stability - new housing technology, uniform codes
1969	Report, Economic (LBJ) - increased Federal Housing R&D; federal testing
1969	Report, First Annual - National Housing Goals - plan for housing construction, economic, land, labor, materials
1969	Address, Inaugural (RMN) - housing is a national goal
1970	Establish, Cabinet Committee on Construction (RMN) - study needs, resources, costs, technology, etc.
1970	Establish, Task Force on Low Income Housing (RMN) - review efforts
1970	Statement (RMN), National Housing Problem - production decline must be stopped; housing top priority
1970	Address, State of Union (RMN) - progress in housing noted
1970	Report, Second Annual - National Housing Goals - construction falling short, begin counting mobile homes
1970	Message, Legislative (RMN) - consolidate low income housing programs, praise "Breakthrough"
1970	Address, N.A.M. (RMN) - housing should lead the economy upward
1971	Address, State of Union (RMN) - absorb HUD into Dept. of Human Resources and Community Development

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B. Other Documents (Cont'd)

1971	Message, Budget - housing has begun to lead economic expansion
1971	Message, Economic - high cost of construction, 40 percent increased starts due to mortgage funds
1971	Proclamation, Suspend Davis Bacon Act - let government construction wages float
1971	Establish, Construction Wage Control Committee - Tripartite to negotiate wages
1971	Proclamation - Reinstate Davis Bacon Act
1971	Executive Order, Energy Efficiency and Environment - HUD will establish insulation standards for FHA homes to reduce heat loss and thus power plant pollution

program by adding the goals of rehabilitation and conservation; the Housing Act of 1965 created the Housing and Urban Development Department, and the Housing Act of 1966 established the Model Cities Program which provided for the use of federal funds to coordinate and finance the rebuilding, both physically and socially, of entire sections of cities. Finally, the Housing Act of 1968 reaffirmed the above-cited 1949 housing goal of "a decent home and suitable living environment for every American family," set the national housing goal shown in Table 4.26 and required the President to submit annual reports to Congress that would show the progress made during each year toward that year's stated goals.

Recent Trends

For a variety of reasons, despite the specific goals set in 1968, national priorities in housing have recently tended to become less clear and less prominent. The close association between the state of the economy and the rate of housing starts, the wave demands of construction labor, a brief shortage of construction materials, and a period of high interest rates have all been elements cutting across the achievement of stated goals. Even the importance of new building technology for the housing program is thrust more in economic than technological or social terms. Thus, it was the Cabinet Committee on Price Stability that, on December 28, 1968, recommended the introduction of new building technology programs to speed the diffusion of this technology throughout the industry; furthermore, calls for increased housing R&D to improve construction technology and for a federal program to test housing materials turned up in the Economic Report of the President (1969).

As inflation persisted, the focus on housing as an economic variable remained prominent. Though a Cabinet Committee on Construction was established in September 1969, and a Task Force on Low Income Housing October 1969, the President, in March 1970, strongly endorsed HUD's Project Breakthrough as an anti-inflation device in a statement entitled, "Combatting Construction Inflation and Meeting Future Construction Needs." Subsequent Presidential statements all stressed the role of construction as a stimulant to the economy generally.[11] This concern went hand-in-hand with attempts to hold down construction labor cost, most recently the suspension, and later reinstatement of the Davis Bacon Act, and the establishment of a tripartite committee to control wages in the construction industry. Thus the social merits of the program have tended to be upstaged by the role of housing as a component of the economy.

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[11] See Budget Message, 1/29/71; Economic Message, 2/1/71; Press Conference, 4/16/71.

Table 4.26 Housing Construction Needs, 1968–1978

	(millions)	
U.S.	Metropolitan	
Units for new households	13.4	10.6
Replacement or rehabilitation of substandard units	8.7	3.5
Replacement of standard removals	3.0	2.1
Allowance for vacancies	1.6	1.2
	26.7	17.4

The Federal Interest in Housing Technology

While the Federal Government's involvement in housing has not been such as to allow the development of technology through contract purchasing, as is characteristic, for ecample, in the electronics, defense, and space industries, it would be wrong to infer that technology was ignored. All of the cited housing legislation contains authority to apply new technologies. In particular, Title III of the Housing Act of 1948, provided authority for housing research concerned with the "application of new technologies, materials and methods to housing." A specific aim of that Act was to aid the prefabricated home industry through loans to assure the industrial capacity for their construction, an aid that in 1951 was broadened to include mobile homes. Much later, when the near-crucial contribution of mobile homes to the achievement of the nation's housing goals was recognized, the Housing and Urban Development Act of 1969 expanded mortgage credit for the purchase of mobile homes and the development of mobile home parks, and a year later the Veterans Housing Act of 1970 gave, for the first time, authority not only for mobile home loans under the Veterans Administration, but for the setting of minimum construction standards for these homes, thus giving an indirect stimulus to technology.

However, this legislation, which since 1948 has authorized various administrations to explore new technologies, has had the most meager of funding. Before 1965, R&D outlays for housing and community development ran below one half million dollars per year. Even now, expenditures amount to only about $45 million, most of it associated with HUD's Project Breakthrough, with one million dollars authorized for the Bureau of Standards to set up a Building Materials Standardization and Testing Program.

This low level of funding for an area that represents one of the nation's primary social goals may indicate uncertainty regarding the potential contribution of Project Breakthrough and of other technology-oriented efforts as compared to the leverage provided by wage and interest rate controls, especially at a time when the housing industry is looked upon to lead the economy. Moreover, with manufacturing costs representing only about one-third of housing costs, even a success here would lower total cost of housing by only one-third the savings in manufacturing cost, unless either financing or land cost were also affected.

Because Project Breakthrough has been HUD's major activity in research and technology, it deserves further analysis. Its goals are to provide incentive to firms to develop and test innovations in housing design construction, land use, financing, management and marketing, and to develop a self-sustaining mechanism for providing volume production of marketable houses at stable or reduced costs for all income groups. Budgets to support these ambitious aspirations were $1.3 million in FY 1970, $36.9 million in FY 1972, and an estimated $16.9 million in FY 1972.

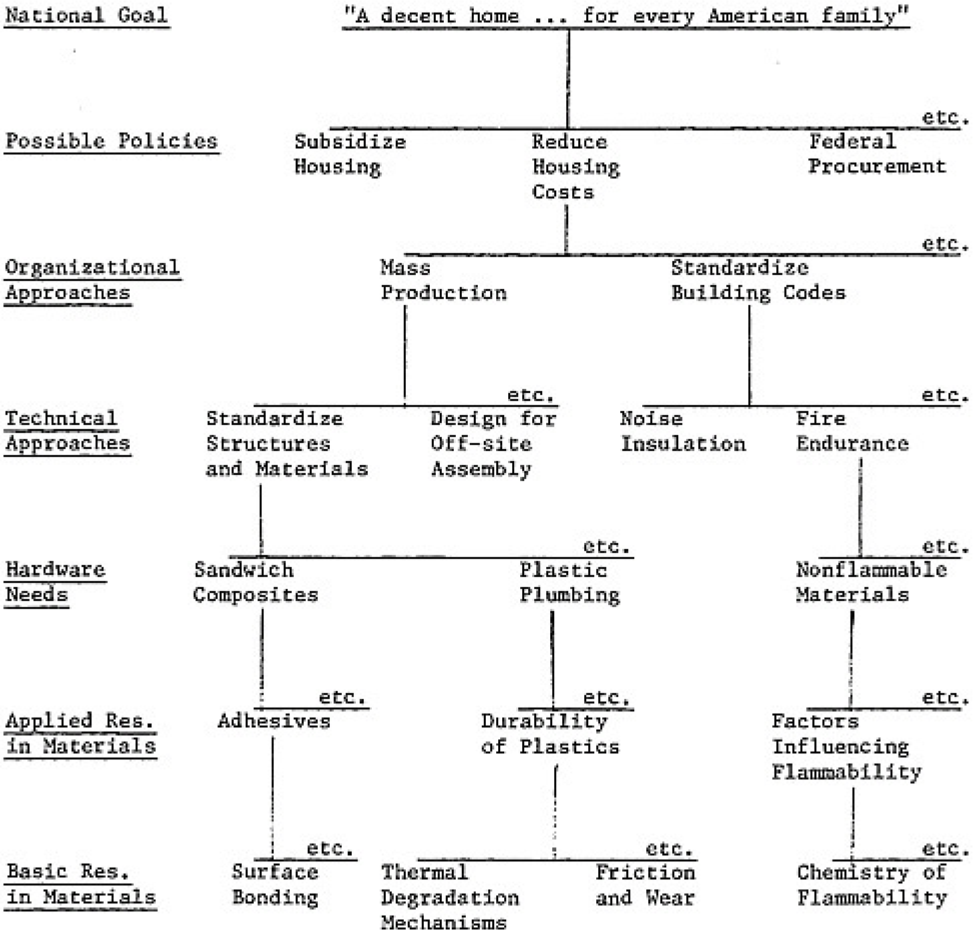
Breakthrough is the most recent evidence of the oscillating federal interest in volume production of marketable housing and the associated unsteadiness in attention to technology and materials. This interest showed up first in the pre-occupation with prefabricated homes. Based largely on experience in World War II, the Housing Act of 1948 placed these under the umbrella of the Housing and Finance Administration; the Housing Act of 1951 broadened this coverage to include mobile or portable homes. Little federal involvement ensued, however, and by 1968 the mobile home had dropped out of federal view as legitimate housing. The 1968 housing goal did not even recognize existence of mobile homes, and the First Annual Report on National Housing Goals submitted to Congress in 1969 did not include any data on mobile homes, even though the growth of public interest in mobile homes was such that in 1969 the number sold represented 20 percent of the annual housing starts. Recognition of the mobile home came in 1970 when it became clear that the housing goals set in 1968 would not be met unless mobile homes were included in the number of housing units produced annually. In the Second Annual Report on National Housing Goals, President Nixon took advantage of the housing windfall to include mobile homes within the definition of acceptable housing units. The large-scale appearance of mobile homes coinciding with the shortage of conventional housing starts undoubtedly contributed to the birth of Operation Breakthrough in 1970 as a research and technology program of HUD. But although Breakthrough was highly publicized, the HUD budget for technology was the same in 1972 as it was in 1971, with the emphasis within the technology program shifting from Operation Breakthrough into other areas, such as developing ways of improving housing management and preventing the deterioration and abandonment of housing, developing municipal and regional information systems for gathering and evaluating data on housing and mortgage markets, applying university resources to urban problems, and improving the environment of communities.

The point here is not, of course, that these developments and activities are unworthy of support. Rather, we note that federal interest in the technology of housing, including the MSE aspects of the industry, was relatively short lived; in fact, technology never occupied a prominent place within the program objectives. Yet, as illustrated in Figure 4.8, specific materials needs can be derived from national housing goals. The succeeding section furnishes some clues to this lack of articulation.

The Housing Industry

The home building industry has been described as a loose conglomeration of small participants who come together on a project-by-project basis. The construction initiator, usually a merchant builder, brings together the architects, engineers, and contractors. The contractor in turn, employs or subcontracts to craftsmen of the plumbing and heating, painting, electrical, masonry, and carpentry trades for the period of their involvement in the on-site construction. Typically, the package dissolves after construction at a given site has been completed. This contrasts with the judgment of an experienced builder, R.M.Wasserman, President of Levitt and Sons who testified in 1968 that "…the most economical method of building homes is the on-site fabrication and assembly of precut lumber in the house structure, and the efficient cycling of men and materials so that a field labor force is kept busy at its trades and not occupied in traveling, handling materials, or waiting for another craft." Levitt reports itself as forced to discard

Figure 4.8 Partial Relevance Tree for Housing



its efficient post-war mass-production techniques of "cookie cutter homes" in favor of homes in accord with marketing rather than production disciplines, which dictate that a variety of homes be built at each site, but has not changed its opinion that field assembly is a most economical method of production, given an adequate supply of skilled labor.

Most on-site building work involves comparatively simple techniques that do not benefit much from scale economies. Many contractors hire all of the plant and equipment required to build and, needing no fixed work place or plant, need only a small amount of capital to enter the contract construction business.

It has been suggested that mass-production techniques will not be employed so long as governments continue to use the housing industry as a regulator of the national economy, since capital-intensive production methods cannot flourish in the climate of housing activities that fluctuate with business conditions.

Capital-intensive, mass-production methods are, of course, employed in the manufacturing of many building materials and components, but the "builder" is an on-site, labor-intensive assembler of components. The debate on industrialized housing thus centers on the nature and extent of these "components" and on the relative amount of on-site vs. off-site labor. The hope, of course, is that the off-site combination of labor and capital will achieve economies over the on-site use of labor alone. In the next section these costs are examined more closely.

Housing Costs

Table 4.27 shows a typical two-way breakdown of costs of housing construction, for three different types of housing. The principal contrast is between on-site-constructed housing and prefabricated homes. In the latter, outlays for materials dominate not only construction cost but amount to over half of total cost.

Costs other than development are further broken down in Table 4.28 for two of these classes.

The cost reductions from off-site assembly are presumably due to three primary factors: (a) lower labor costs of manufacturing vs. craft union workers, (b) continuity of labor in factory vs. site (continuity of work and independence from weather), and (c) application of capital-intensive operations to expedite manufacturing and assembly in plant.

Obstacles to off-site prefabrication are well-known. They are, briefly, the still unsavory marketing image of "prefabs;" the variety of building codes; and the need to transport large bulky items. The last obstacle especially handicaps prefabricated concrete technology, and limits sales of prefabricated frame construction to a range of about 300 miles.

The net effect is to discourage capital investment in industrialized housing until such time as it becomes clear that the investment can be amortized over a large enough production volume. The potential success of a project like Breakthrough lies in its ability to guarantee a market for a known number of experimental housing units, thus justifying at least limited private investment in the manufacturing capacity.

Table 4.27 Relative Shares of Development & Construction Costs in Different Types of Housing

	One-Family Development Home	Multi-Storied Apartment	Pre-fab One-family
Development (including brokerage, legal, architectural, marketing, etc.)	31%	25%	34%
Construction, Materials	37%	38%	58%
On-site wages	18%	22%	4%
Overhead/profit	14%	15%	4%

Table 4.28 Relative Shares of Specific Construction Cost

	One Fam. Develop. ($11,165)	Pre-fab. One Fam. ($9,660)
Framing, Roofing, Wallboard	21.5%	16.5%
Rough Plumbing, Heating, Elect.	16.5%	11.5%
Interior and Appliances	17.5%	21%
Foundation, Excavation, Septic	11.5%	12.5%
Blacktop, Landscaping	2%	2.5%
	69%	64%
		OF TOTAL COST

The reduced cost/sq. ft. of the mobile home, which is completely assembled off-site, is attributed partly to industrialized construction and partly to reduced design life. The typical financing period for mobile homes is seven years in contrast to 25–30 for a conventional home.

Once sited, these “mobile” homes are rarely moved, staying in one location for an average of 58 months which is about the same length of time that residents occupy one conventional home. The monthly costs are also about the same as a conventional home, due largely to the shorter financing period and to the lot-rental charges.

Directions in Housing Technology

In spite of all these obstacles, there is a fair chance that to achieve the national housing goals and benefit from the economies of mass construction, the next decade may witness the emergence of industrialized housing. The twenty-two housing prototypes developed under contract with HUD are being evaluated by the Building Research Division of the National Bureau of Standards. From these evaluations should flow a new basis for residential construction acceptability, namely performance criteria. These criteria will specify the levels of safety, durability, healthfulness, and liveability, but will leave the methods of design and material selection to the builder. The expectation is that the substitution of performance criteria for building codes will permit the development of modular building systems composed of standard components capable of assembly into a variety of configurations. Thus, economies of scale can be achieved in the manufacture of relatively complex prefabricated components while on-site assemblies will require only a limited amount of labor. An attempt is made in Table 4.29 to relate materials development to housing applications, as they have occurred in the past.

Materials developments are most likely to follow the demands of industrial construction processes. Present materials such as gypsum board, plywood, concrete, glass, and aluminum, manufactured as specialties by the major materials-producing firms, are remarkably inexpensive in contrast to other synthetic materials and are unlikely to be displaced in their present functions. Materials development and application efforts are carried out by the materials suppliers and, in the case of wood products and concrete, by the Forest Products Laboratory of USDA and the Portland Cement Association, respectively. A serious problem being examined by a number of laboratories is that of finding materials capable of joining the modules in a satisfactory way for long-term service. The fire-retardation properties of synthetic materials will also require improvement before they can enjoy extensive application in housing. As everywhere, the introduction of a new material of higher cost can only be justified if the overall assembly performance offset the increased cost. In the case of housing, the economies will most likely be derived from off-site manufacturing processes, and until such time the introduction of novel construction materials will be inhibited.

Table 4.29 Past Materials Innovations in Housing Technology

Material	Housing Application
plywood	sheeting
gypsum board	dry wall const,
concrete—polyester concrete	foundations, const.
concrete block—precast	foundations, bldg.
glass	windows
fiberglass	insulation, panels
aluminum	vapor barrier, window frames, siding
polymers	paints, adhesives, sealants
structural sandwiches	panels
steel alloys	apt. framing
manufactured board	mouldings, etc.
composites (gypsum, fiberglass, paper)	panels

Opportunities for Materials Innovation

Roadblocks

Dispersion—Because of its huge size and its extremely diffuse nature, the introduction of any innovation into the building industry is, typically, a slow process. One association alone lists more than 40,000 home builders; there are more than 20,000 registered architects; approximately 80,000 engineers work in some phase of building; there are several hundred thousand general contractors; and the numbers of people in finance, real estate, and similar activities run to the hundreds of thousands. In a fragmented industry such as this, widely diffused and ancient, tradition has a strong influence and yields slowly to change, not so much because of stubbornness, as because of the immense effort required to introduce new concepts and materials.

Codes—Although their role in impeding progress is often grossly overstated, it is true that building codes act as a brake on progress, not so much because they are archaic and out-of-date, as many of them are, but because they vary greatly, and these differences make difficult the widespread adoption of new ideas. It is estimated that there are 4,000 to 6,000 separate municipal building codes in the U.S. This comes about because under the Constitution, the police power is regulated to the states, and the states, in turn, have passed on down the power of writing building codes. However, there are efforts to develop or suggest uniform building codes by a number of national building officials, standards associations, and insurance associations that likewise promulgate codes. Several states have set up suggested building codes which have been adopted by numerous municipalities within those states. There is, however, nothing approaching a uniform national code, nor is there likely to be in the near future.

Educating an industry of this size and nature in the value and properties of a new material and its use is an immense undertaking. Even greater is the effort required to market the material and to make it available to local builders as needed. Materials must flow through the pipelines to existing outlets, or else a new set of outlets must be established for materials to be used in housing and urban renewal.

The mobile home industry provides a sharp contrast. By considering the home a transportation vehicle, traditional home-building codes are avoided and more flexibility is available in the material selection and assembly techniques. For mobile homes, materials can be chosen to meet specified functions rather than to follow long traditions. Even so, there has not been a spectacular emergence of new families of materials. Substances such as aluminum sheet, plywood, hardboard, cement-asbestos, fiberboard, and other familiar materials are in common use.

Perhaps the most advanced concepts occur with the bath. Traditional cast iron and procelain are too heavy and subject to cracking. Reinforced plastics, mainly glass fiber reinforced polyesters with get coats, are now widely adopted. They are light, tough, and strong, and can withstand the handling and racking involved in assembly and transportation. They do scratch more readily than porcelain and are subject to cigarette stains and charring.

Long-Life Requirements—Unlike the materials for numerous engineering applications, materials for building must have a long life. Whereas five to ten years may constitute old age for service in many fields, this constitutes a mere beginning for most building applications. In housing, where mortgages run commonly for forty years, materials are expected to last at least that long and, generally, much longer. New materials, therefore, must be introduced with the assurance that they will provide such longevity under the great range of climatic and use conditions to which buildings are subjected. It is true that some components of buildings are not expected to last that long and are renewed at shorter intervals. It is true, also, that architects are beginning to recognize the situation and to design their buildings so that portions of them, such as the structure, are expected to last throughout the life of the building, whereas other components such as parts of the mechanical and electrical systems are expected to become obsolete before that time; and still other portions, such as interior finish, may be expected to be renewed at, perhaps, five- to ten-year intervals. Five years, however, is a very short time for any building component to wear out.

Customer Preference—Very few materials applications are influenced by customer preferences as strongly as building materials. This is particularly true of housing which is often the largest single investment that a family makes. Consequently, contractors are likely to be extremely conservative in their choices of materials, partly because they are accustomed to them and partly because of fear that anything radically different will not have a ready market in case of resale. It is true, also, that in too many cases, new materials have failed to behave as satisfactorily as the traditional materials and the general public is understandably suspicious. Remarks such as, “Anything is fine so long as it’s brick,” “None of those concrete prisons,” “None of that ticky-tacky,” are indicative of consumer preference. The single-family house is firmly established in the American tradition and attempts to change it, even when the changes have been in the direction of greater durability and less maintenance, have not met with outstanding success. This attitude applies mainly to those materials which are readily visible and with which the public comes into direct contact. Concealed items such as structural frame, insulation, vapor barriers, and so forth, can more readily be different. This is one of the compelling reasons why new materials are frequently made to resemble traditional materials as much as possible. Aluminum and plastic clopboards are a case in point; so are woodgrained cement-asbestos shingles.

Materials Development

Building materials are customarily developed by materials manufacturers serving the building industry and not by the construction branch of the industry as such. Builders utilize the materials supplied them by the manufacturers; architects and engineers design with those materials and carry on little or no materials development themselves. Many of the conventional materials, particularly those that are heavy and low cost and, therefore, must be produced locally, are manufactured by relatively smallscale producers who do not have the resources or the ability to carry on R&D.

They tend to produce the traditional materials in the traditional ways and market them through the traditional outlets.

Large-scale manufacturers, on the other hand, do have the resources for R&D and many of them support extensive programs. Even here, however, basic research is usually on a relatively modest scale compared to the development of materials for the immediate market. A few manufacturers carry on basic physical and mechanical research into the properties of their materials, and maintain development staffs to explore applications of the findings emanating from the laboratories. These laboratories are also in touch with research being carried on elsewhere, such as in the universities, government research laboratories. They have not been notable, however, for support of basic research at the universities and elsewhere.

Some governmental agencies have done good work in materials. An outstanding one is the Forest Products Laboratory of the U.S. Department of Agriculture which has carried on pioneering work in basic structure of wood and in its applications to building. Many of the developments in wood technology have stemmed from work at this laboratory.

The U.S. National Bureau of Standards, similarly, in its Building Research Division, has carried out basic work on the science of building materials and the technology of their application. Association laboratories, such as that of the Portland Cement Association, have similarly made important contributions. Nevertheless, compared to the overall volume of building, the proportion spent on building research, including research in materials, is small —often quoted as 0.1% of sales compared to 1.9% for stone, clay, and glass products or 3.4% for fabricated metal products.

Those materials manufacturers that do carry on research and development programs realize that they are in strong competition with traditional materials and with other manufacturers. Consequently, they are characteristically aggressive in promoting their new products and are in close touch with what is going on in the construction industry. Even for them, however, extensive marketing efforts are required to introduce new materials and concepts to the building field.

Examples of Materials Development in the Industry

Plastics-Based Materials

Although the volume of plastics materials employed in buildings is small and constitutes only a few percent of the total, the number of uses is constantly increasing, and the building field is continually being probed to find new applications for plastics and other polymeric-based materials.

One example is polyester concrete. When polyester is substituted for Portland cement in the manufacture of concrete involving properly-selected aggregates such as silica sand, the resulting concrete is considerably higher in tensile strength than ordinary portland cement concrete and is comparable in compressive strength and stiffness. It can be cast in a mold, in much the same way as the portland cement concrete, but it has the advantage that, generally, it cures overnight and is ready to use the next day, whereas portland cement concrete requires 21 to 28 days for complete curing. The polyester concrete appears to weather well, on the basis of only eight to ten years of exposure, and to undergo fine cracking less than does portland cement concrete. However, it is more expensive per unit volume than the traditional concrete. In a hot fire, there will be some smoke evolution and, obviously, it does not have the long-time history of portland cement concrete. The cost differential can be offset by the fact that thinner sections can be employed.

Polymeric materials are creating a considerable revolution in the field of decorative and protective coatings. Traditional, clear-cut boundaries between coatings, including paint, varnish, lacquer, and builders' enamel are becoming blurred as new polymers are introduced; emulsions take the place of drying oils, and new combinations of solvents and resins have been developed. The same is true of adhesives wherein the new, high-strength, waterproof adhesives are based on plastics and polymeric materials. The caulking compounds, sealants, and gaskets widely employed for installing large sheets of glass and precast or otherwise-prefabricated components, are largely based upon the elastomeric polymers. Emulsions of these materials added to mortar develop high tensile strength and high bond strength, and make it possible to utilize not only thinner masonry walls but masonry panels which can be prelaid on the ground and hoisted into place. Increased strength and toughness are imparted to plasters and stucco by similar means.

Structural Sandwiches

One of the more intriguing developments of the post World War II years has been the gradual increase in the use of structural sandwiches. In these panels, relatively thin, strong, dense facings are combined with relatively thick, lighter-weight cores to provide a combination of geometry and materials which results in combined strength, stiffness, light weight, and insulation. For example, the polyester concrete mentioned above may be used in layers from 3/4 to 1-inch thick as facings combined with a core of an efficient thermal insulating foam, such as polyurethane, to produce building panels only two to three inches in thickness which have the necessary strength, stiffness, and insulating value.

Panels developed for the Greater London Council are a case in point. The Council merely set forth performance requirements with respect to windloading, thermal transmission, acoustical isolation value, flamespread and fire-penetration limitations, minimum weight, minimum thickness, and minimum maintenance, without specifying materials. Out of the requirements emerged a building panel consisting of an outer shell of glass-fiber-reinforced polyester with a baked-on polyurethane finish, a core of concrete foam, and an inner facing of reinforced gypsum. The foan was bonded to the shell with a flexible synthetic adhesive bond, and the gypsum was bonded to the foam with a layer of bitumen which simultaneously acted as a vapor barrier. The overall panel had all of the requirements, weighed approximately 15 to 20 percent of the standard construction, and was approximately one-third as thick. The estimated in-place cost, for a total of 12 buildings to justify the cost of production equipment, was comparable with conventional construction, partly because of reduced weight, reduced structural steel, reduced footings, and greatly increased speed of erection. This is an example of successful MSE that can occur when performance is set forth rather than prescriptive specifications. As building codes gradually evolve in the direction of performance rather than prescriptive codes, as enforcement agencies become sophisticated enough to handle such codes, and as designers become accustomed to thinking in terms of performance, it may be expected that composite uses of materials, as exemplified by the building sandwiches, will increase. It is to be noted, however, that the necessary social, economic, and political conditions must be present to allow such developments to occur.

Encouragement of Innovation

Innovative ideas, whether they relate to materials or other building components, have a hard time getting adopted partly because there is no accepted means of evaluating and certifying innovations. The individual with the bright new idea, no matter how good it may be, is faced with a long, arduous process for obtaining acceptance. There is, for example, no generally recognized testing agency. The innovators are faced with finding a university, private testing laboratory, or other organization to run tests. Even when this is done and the results are successful, the innovator is faced with the formidable task of convincing building code officials, architects, engineers, builders, financiers, and owners of the efficacy of his idea. It is no wonder, therefore, that unless he is exceptionally well financed, his idea may very well die before it has a chance to be tried.

Some central agency, probably neither governmental nor completely private, is needed that has the expertise and the confidence of the building fraternity, to which an innovator can turn with his idea to have it examined, tests prescribed, evaluated, and certified as useful with whatever curbs and constraints may be necessary in the opinion of the agency. With this kind of certification, the innovator would have a much easier time in getting his idea tried. Examples exist in a number of European countries and have, in many cases, been notably successful. Whether the European counterparts should be adopted completely in the U.S. is, perhaps, problematical, but some kind of certification could be helpful in reducing the extremely difficult problem of gaining acceptance.

Prediction of Behavior

A major stumbling block to the adoption of new materials in the housing industry is the question of predicting long-time behavior on the basis of short-time tests. This is difficult, if not practically impossible in many cases, particularly for such critical problems as weathering. Completely reliable weathering tests which will satisfactorily predict the long-time behavior of materials are yet to be developed. This is a major technical issue and one which could well challenge the best efforts of materials scientists and engineers; it is a major deterrent to the adoption of new materials.

Associated with the development of reliable testing methods is the need for the careful, comprehensive evaluation of existing installations. Although there is a good deal of scattered and relatively uncorrelated information regarding the behavior of materials and building components in actual service, a really systematic and thoroughly organized survey, readily available to all parts of the industry, does not exist. Evidently, this kind of information is basic, not only to the utilization of the existing materials, but to the prediction of the behavior of new materials and the development of tests.

Fire Endurance

The prediction of behavior of materials in building fires is in serious need of better understanding. Correlation between laboratory tests and actual building fires has to be greatly improved. Speed of ignition, rate of flamespread, smoke evolution, and penetration of fire through barriers such as walls and partitions are all measured by relatively empirical laboratory tests, but there is considerable doubt concerning the test results even though many of them are written into building codes for lack of something better. Most attention, until recently, has been focused on flame, flammability, flamespread, and flame penetration. Recently, partly because of the introduction of new materials, it has been realized that smoke evolution and the development of toxic or irritating gases may be more dangerous than actual flame in causing loss of life. The evolution of smoke and gases is even less well understood than the onset of flame. It is known that the same materials may behave quite differently in different kinds of fires, giving off dense smoke in some cases and practically none in others, depending upon temperature, oxygen availability, and still other factors. Here is another field where the transition should be made from empiricism and experience to a groundwork of scientific understanding, closely coupled with engineering application.

NOTE ON NEEDS IN CONSUMER GOODS, PRODUCTION EQUIPMENT, AND AUTOMATION

In addition to the preceding studies of the relations between MSE and various national goals, some less complete studies were made of the opportunities for materials R&D relating to consumer goods and production equipment. In connection with consumer goods, there is the persistent need for greater durability (both physical and chemical), less flammability, and greater safety, reliability, serviceability, and maintainability. A clear need exists also for better tests for these characteristics. Materials problems relevant to production equipment include longer-lasting, higher-speed machining devices, both metallic and ceramic (e.g., grinding wheels), better joining methods, and greater high-temperature strength.

There are attractive opportunities in a special area of production equipment: automation and robotics. These opportunities exist not only in production and manufacturing, but also throughout the service areas of the economy—mail sorting, billing, typesetting, weather forecasting, health checkups, traffic control. Automation techniques in all of these directions include a common approach: the generation and processing of information to provide or display data in useful forms or to control servomechanisms. Myriad possibilities can be discerned in primary information-generating devices or sensors, which will depend on the nature of the physical property to be measured, the object to be sensed, or the pattern to be diagnosed. Nearly always these sensing techniques must be nondestructive. They must rely, therefore, on the effects of the interaction of matter with various kinds of radiation—optical, electromagnetic, ultrasonic, and others. Progress in this field clearly will require the most sophisticated knowledge of materials and of spectroscopy in its broadest sense.

The signals generated by the primary sensing device usually must be processed, analyzed, and correlated by a computer or, increasingly, a mini-computer, itself a product of modern MSE in its integrated circuits and memory devices. Once in useful form, the information can be printed out, visually displayed, or used to control a machine or servomechanism. Prospects for improvement lie both in visual displays and in computer-controlled machines. The latter can range from simple mechanical transducers—to control a valve, for example—to complex robots that can simulate some of the routine actions of human beings.

The development of this type of automation will require new devices, particularly optoelectronic, and solid-state electronic circuits with associative memory and learning capability for parallel processing. Especially promising avenues for further research appear to be semiconductor lasers and light-emitting diodes, magnetic-bubble devices, charge-coupled devices, reversible photosensitive materials, liquid crystals, optical modulators and deflectors, and various functional components such as amplifiers, timing circuits, and shift registers. Advances in servomechanism design will call for the combined talents of electrical and mechanical engineers, but often these devices and machines will also place stringent demands on the materials of which they are made, especially when the equipment must work reliably for long periods in hostile environments.

Automation is a very broad interdisciplinary area and is likely to become more so. It embraces the knowledge and skills of materials scientists and engineers with those of the information community—mathematics and statisticians, as well as computer-hardware and software engineers. The economic and social implications of switching to automation in a given operation, moreover, can call also for the expertise of economists and social scientists.

CHALLENGES IN THE MATERIALS CYCLE

Today we are faced with growing competition for nonrenewable raw materials and fuels, as well as with low standards of living in much of the world. The latter is an old problem, but it is reemerging in a new setting that prominently features the aspirations of the developing countries, concern for the environment, and the scale of international human activities. These difficulties, in consequence, are attracting more and more attention, both in the U.S. and abroad, shifting to a degree the emphasis on national defense and political prestige toward more civilian-oriented goals and concerns.

Materials science and engineering can help meet the technical challenges of these growing concerns. By providing options at the various stages in the materials cycle, it can exert direct, if not always immediately visible, effects in the problem areas reflected by national concerns. It can help to slow and sometimes to halt the growth in demand for certain raw materials and fuels. It can help to move hardware technologies in directions that raise living standards at home and abroad. It can help to reduce deleterious effects on the environment to acceptable levels. And it can help to achieve these goals in a manner consistent with a sound U.S. balance of trade.

Exploration

The sensing, information-processing, and transmitting functions of orbiting earth-resources satellites and lunar rovers were made possible by progress in development of electronic and structural materials. Comparable technology could be developed for exploring the ocean floor. For more traditional types of prospecting, instrumental methods should progress rapidly as more is learned of the “signatures” of complex natural materials.

Mining

Ores and minerals in the future probably will have to be mined in more hostile environments at less accessible sites. (Manganese and other metals, as well as phosphates, for example, are available on the ocean floor.) Working conditions often may be impossible for human operators. To tap the resources available from ultradeep mines or even below the ocean floor will require a new technology, “robotics.” In essence, robotics will involve solid-state electronic sensing and information-processing equipment coupled to servomechanical mechanisms that can operate under extreme conditions. The advent of novel equipment of this kind likewise will benefit conventional mining operations. Plasma and rocket-nozzle technology, for instance, has proved useful in drilling the hard, iron-bearing taconite—which has largely succeeded the heavily-depleted, high-grade domestic iron ore that was long the mainstay of the nation’s steel industry.

Extraction

We need very much to find new means of extracting basic materials from ores of progressively lower grade and from low-grade wastes, processes that are more efficient, that cost less, consume less energy, and cause less pollution. Aluminum already is being extracted from the abundant anorthosite (in the Soviet Union) as opposed to the conventional source, the high-grade but less plentiful bauxite. Under development in the U.S. are two new aluminum processes: one reduces by about a third the energy required to produce aluminum from alumina by electrolysis; the other produces aluminum in several (nonelectrolytic) steps, starting with various sources of the metal—not only bauxite, but low-grade alumina-bearing minerals and even clay. The large piles of blast-furnace and open-hearth slag in the Midwest are potential sources of manganese and phosphate. Longer-range possibilities include simultaneous extraction—perhaps at very high temperature—of several materials from “ores” like granite, which contains all the elements necessary to a modern industrial society. For higher-value materials, study seems warranted on electrostatic, electrophoretic, and other novel methods of separation.

Renewable Resources

Considerable scope exists for expanding the range of materials obtained from renewable resources. Wood and vegetable fibers might become important sources of primary organic chemicals, although they are not economically competitive today. Means of “cracking” the lignin molecule, the binding material in trees, could make organic chemicals available from about 25 million tons of lignin disposed of annually in this country in wood wastes with only minor recovery of values. The utility of renewable resources in general might be extended by a variety of methods: better chemical means of recovering basic materials; control of physical properties by chemical or radiation treatment; genetic modification during growth; new ways to make composite materials of natural products; and improved methods of protecting and preserving structural materials made of natural products.

Resource Substitution

The substitution of plentiful for less-plentiful resources is likely to become an especially important task for MSE in the future. A material may be substituted for another of the same class, as when aluminum replaces copper in electrical conductors, or for one of a different class, as when polyethylene replaces galvanized steel in buckets. We will need substitutes for certain metals that have unique and important properties but threaten to become critically scarce in the not-so-distant future. These include gold, mercury, and palladium. The nation’s balance of trade would benefit from substituting manganese for nickel as a stabilizer in stainless steels and substituting domestic ilmenite for imported rutile as a source of titanium.

Even metals and alloys used widely in structural applications may offer broad scope for substitution by other alloys or ceramics based on substances more abundant in nature. The most common substance in the earth's crust is silicon dioxide. It is a basic constituent of glasses, which are remarkably versatile materials used hardly at all in proportion to their potential abundance. The properties of glass include excellent corrosion resistance and very high intrinsic strength. Aluminum and magnesium—though the energy cost of obtaining them is relatively high—are abundant and display useful properties. These include, especially, the high ratios of strength-to-weight so important in engineering applications.

Processing, Manufacturing

Widespread opportunity exists for new processing and manufacturing techniques that waste less material and use less energy than do current methods. More processes are needed that lead directly from liquids and powders to finished shapes, thereby avoiding, for metals, the ingot and hot-working states. Such processes tend to cost less and consume less energy than do the cold-forming and machining required to shape bulk solids. Industry already shapes liquid or powders in many cases: manufacture of float glass, slip casting or compacting of intricate shapes, die casting and plastic molding, and hot forging of sintered metals.

Continuous on-line assembly with minimum human intervention, a continuing objective for production lines, is virtually achieved in the manufacture of integrated circuits, where relatively few of the 200 or more processing steps are controlled actively by operators. The approach should be extended to other areas of processing and manufacturing. Some of the greatest savings in production costs and resources probably will result in the long run from greater use of small on-line computers and robots. This form of the robotics mentioned earlier for mining calls for the imaginative exploitation of a variety of sensing and monitoring devices coupled through minicomputers to control mechanisms.

Environmental Effects

The need to preserve the environment requires continuing development of industrial processes that release fewer harmful effluents or effluents which can be captured and converted to harmless and preferably useful forms. Some such processes are used widely now. One is the recovery of sulfur from petroleum refinery off-gases. Another is the recycling of the hydrochloric acid that has been displacing the nonrecyclable sulfuric acid in the pickling of steel for cold forming. The heavy, hard-rubber cases of automobile storage batteries are not reused and often are disposed of by burning; a lighter-weight, reusable plastic case would seem feasible. The metallic salts in polyvinyl chloride film may become an air-pollution hazard when the discarded film is burned, as in an incinerator; alternatives to the salts should be considered. To improve health and safety inside the plant, it is likely that one of the most effective moves will be wider use of robotics where working conditions are not suitable for humans.

Improved Performance

The purpose of MSE historically has been to improve performance by modifying existing materials and developing new ones. This activity will remain important. Demand will continue for higher-performance alloys, tougher glass and ceramics, stronger and tougher composites, greater magnetic strengths. But the task grows more complex as performance criteria come to embrace chemical and biological as well as mechanical and physical properties. Consumers and legislation, furthermore, are calling increasingly for materials and products that are more durable, more reliable, safer, and less toxic. To meet these requirements, a number of complex, materials-related phenomena must be elucidated. They include corrosion, flammability, thermal and photodegradation, creep and fatigue, electromigration and electrochemical action, and biological behavior.

Functional Substitution

Functional substitution offers great opportunity in MSE. The aim is not simply to replace one material with a better one, but to find a whole new way to do a given job. To join two metals, for example, one can develop not just stronger nuts and bolts, but adhesives. Jet engines replace piston engines and propellers in aircraft; telephones replace the mails for transmitting information. Functional substitution can lead to the revision of consumption patterns for materials and energy and, indeed, can inspire the creation of entirely new industries. Widespread use of nuclear or solar energy could yield enormous savings in the transportation of fossil fuels. The transistor started the solid-state electronics industry, which has led to technologies like computers, missile-control systems, and a broad range of industrial, medical, and leisure products. Challenging problems for functional substitution include: developing materials and techniques for new methods of generating and storing electrical energy; and finding functional substitutes and biological materials to replace human organs.

Product Design

The better we understand the properties of materials and how to control them, the more efficiently we can design them into products, provided that materials and design specialists work closely together from the beginning of the design and development process. The resulting interplay may change apparent design restrictions radically and achieve more effective solutions to the design problem. Purposeful blending of materials and design expertise, moreover, can contribute significantly to conservation of materials. Appropriate knowledge sometimes allows safety margins to be narrowed without hazard, thus reducing the weight of material needed in the product. Where properties like strength and elastic modulus can be upgraded, the product can sometimes be made to contain significantly less material without corresponding loss in performance. An example is the use of textured steel sheet in automobile bodies. Design can also be improved as a result of clarifying the functional requirements of specific parts of a product. For example, if only a surface must resist corrosion, coating or cladding may require less material and cost less than use of corrosion-resistant material throughout.

Recovery, Recycling

Facilitating the recovery and recycling of materials—apart from new approaches to questions like collection and separation—presents broad new problems in product design and materials selection. Product designs should ease dismantling and separation of components, but the rising costs of repair services tend to favor materials and products designed for replacement as whole units rather than for dismantling and repair. These conflicting pressures will have to be reconciled. Metals like those in a shredded automobile tend to be degraded with each recycle, although they may be quite suitable for applications less demanding than the original ones. The same is true of blended plastics, ceramics, composites, and glass. It is not clear that these problems can be solved without sacrificing performance. We must learn not only to recycle materials more efficiently; we must develop secondary and tertiary outlets for recycled materials whose properties no longer meet the requirements of the primary functions. Extractive chemistry and metallurgy will be important in improving recycling processes, but better physical methods of separation are needed, too.

PRIORITIES IN GOAL-ORIENTED MATERIALS RESEARCH

A study of priorities in materials research, described in detail in Chapter 5, revealed many topics having high priority for important advances in the areas of impact covered in this chapter. In particular, these priorities, which are given in Table 4.30, were obtained from analysis of several thousand write-in comments from materials professionals.

Table 4.30 Goal-Oriented Materials Research Bearing on Areas of National Impact

(Where applications are listed, the meaning, generally, is that new materials and processes are needed to advance the application.)

Communications, Computers, and Control

Memories; visual displays, semiconductors, thin films; integrated circuit processes, yields in large scale integration, component reliability; optical communication systems; defect properties of crystals; chemical and surface properties of electronic materials; purification; crystal growth and epitaxy; joining techniques; contacts; high temperature semiconductors.

Consumer Goods

Durability; visual displays; corrosion; mechanical properties; improved strength-to-weight packaging; recyclable containers; high-strength glass; plastics; plastic processing; composites.

Defense and Space

Mechanical properties; lasers and optical devices; energy sources; heat resistance; corrosion; radiation-damage-resistant electronics; composites; turbine blades; heat shields; thermal-control coatings; nondestructive testing; higher joining strength-to-weight-ratio materials; reliability; materials for deep-sea vehicles.

Energy

Battery electrodes; solid state electrolytes; seals; superconductors; electrical insulators; mechanical properties; radiation damage; high-temperature materials; corrosion; joining; nondestructive testing.

Environmental Quality

Less-polluting materials processes; pollution standards; recyclability; reduced safety and health hazards; extraction processes; catalysts; secondary uses for discarded materials; sorting processes; nondestructive testing; noise reduction.

Health Services

Implant materials; membranes; biocompatibility; medical sensors; material degradation.

Housing and Other Construction
Prefabrication techniques; corrosion; cement and concrete; weatherability; flammability.
Production Equipment
Friction and wear; corrosion; sensors; automation.
Transportation Equipment
Corrosion; pollution control; high strength-to-weight ratios; high-strength, high temperature materials; impact resistance; catalysts; adhesives; superconductors; lubricants.

CHAPTER 5

PRIORITIES IN MATERIALS RESEARCH*

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*This chapter, which is primarily the work of Kenneth A.Jackson and A.G. Chynoweth, is based entirely on the many hundreds of replies to a questionnaire which was devised by COSMAT Panel VI and sent out to a large selection of scientists and engineers representative of the field of materials science and engineering.

CHAPTER 5

PRIORITIES IN MATERIALS RESEARCH

COSMAT PRIORITY SURVEY

As part of the COSMAT study of the field of Materials Science and Engineering, a survey of various professionals in the field was conducted. The purpose of this survey was to gather information on areas of priority for basic and applied research. The breadth and scope of the responses was impressive. Materials are so diversely used in our society that no one person or indeed any small group of people could have information on the variety of materials and their uses which were present in the responses to the survey. The survey has succeeded admirably in obtaining a broad-based assessment of the current state-of-the-art for the wide range of materials, properties, processes and disciplines which make up Materials Science and Engineering.

This chapter is a detailed report on the responses to the Survey. The survey solicited some broad overall assessments but took into account the fact that few people have detailed knowledge of the whole spectrum of Materials Science activity. The Survey therefore asked for detailed responses only in a few areas selected by the respondee. The questionnaire was designed so that various cross correlations and sub-groupings of the responses could be selected for analysis.

The survey was divided into two main parts: One of these asked for an assessment of priorities for Basic Research; the other part, for Applied Research and Engineering. In this latter part, the priorities will depend on the area of intended application, which were grouped into nine major areas of impact. Each area of impact was in turn subdivided into various sub-areas of impact, and the respondees were asked to rate priorities in up to five of these. As will be seen from the responses below, priorities differ widely from one area of impact to another and even amongst the sub-areas.

In addition to providing a numerical rating of priorities, the respondees also provided comments on various areas of importance. These comments are also presented here to supplement the numerical ratings.

The Questionnaire

The questionnaire was accompanied by a cover letter, signed by M.Cohen and W.O.Baker, a copy of which is included in Appendix 5A. The instruction sheet for filling out the questionnaire, and the list of Areas and Sub-areas of Impact are also in Appendix 5A. The questionnaire (also included in Appendix 5A) began (page 1) by asking for a ranking on a 1 to 5 scale of the overall importance of Materials Science and Engineering to each area of impact. On page 2, the respondees were asked to select up to five sub-areas of impact, with which they were familiar, and to list materials problems which they judged of critical importance in each. These responses are summarized below.

The respondees were then asked to rate priorities for each of the subareas selected on page 2 according to Properties of Materials (page 3), Classes of Materials (page 4), Processes for Materials (page 5) and Disciplines and Sub-disciplines in the Field of Materials Science and Engineering (page 6). They were also asked to rate their familiarity with each Property, Material, Process and Discipline. A rating of level of priority for Basic Research for each Property, Material and Process was requested on the right hand side of pages 3, 4 and 5, along with a brief statement of the nature of the basic research. The last page of the questionnaire asked for personal information for statistical purposes.

Some 2800 copies of the questionnaire were mailed, using the names on the lists which are included in Appendix 5A. These lists were chosen in order to obtain a broad but in-depth coverage of Materials Science and Engineering. In all, 555 useful questionnaires were returned. Each respondee was asked to provide up to 451 answers or rankings, which would require an hour or more to do. Not all of these were completely filled in. The responses were computerized for analysis.

A rating scale was adopted to determine the average response to a question. The questionnaire asked for responses on a scale of 1 to 5, where 1 indicated great importance and 5 indicated little importance. The responses of this type have been converted to a 0 to 100 scale, where 100 corresponds to all responses being “1” and 0 corresponds to all responses being “5”.

The rating number used to report these responses is given by:

$$\frac{100\langle 1\rangle + 75\langle 2\rangle + 50\langle 3\rangle + 25\langle 4\rangle}{\langle 1\rangle + \langle 2\rangle + \langle 3\rangle + \langle 4\rangle + \langle 5\rangle}$$

where <1> is the number of “1” responses, <2> is the number of “2” responses and so on. Blank responses were not counted.

The Respondees

On the last page of the questionnaire personal information about the respondees was requested for statistical purposes, to provide information about the background of those who responded to the questionnaire. A summary of the responses to the personal information is shown in Table 5.1a. Most of the respondees have Ph.D.'s and are over forty years old. The respondees are fairly uniformly distributed between academia, government laboratories and industrial laboratories with a much smaller fraction being in non-profit organizations and "other". Most of the people are engaged in research or in technical management but there is also a good representation of teachers and those engaged in development or engineering work as well as a significant number in general management. The respondees could check more than one category in this section, so the totals exceed the total number of respondees. About half of the managers have between 10 and 100 people reporting to them with about a quarter of them having less than 10 and a quarter having more than 100 people reporting to them. The discipline in which the respondees obtained their highest degree are shown in Table 5.1b, according to the responses which they wrote in. These have been divided into four main groups, the largest of which can be called Metallurgy but includes Physical Metallurgy, Earth Sciences, Ceramics and the newer discipline of Materials Science. The next largest group is Physics followed by Chemistry and the fourth category is Engineering which includes a variety of engineers.

The average age and educational level of the respondees are as expected in view of the lists which were used for mailing the questionnaire. The respondees typically have advanced scientific training and have reached a fairly mature stage of their careers. They are fairly evenly divided amongst the disciplines of Physics, Chemistry, Metallurgy and Engineering. This seems to be a fairly typical distribution for those involved in Materials Science and Engineering. We believe this cross section and this group of people to be fairly optimal for assessing the current priorities in Materials Science and Engineering.

TABLE 5.1a Personal Information

Highest Degree:
None 0, Bachelor 62, Master 78, Ph.D. 379.
Age Bracket:
Under 30 5, 30–39 74, 40–49 214, 50 & up 262.
Employment:
a) Type of Institution:
Academic 187, Government 120, Industrial 215, Non-Profit 16, Other 17.
b) Type of Activity:
Teaching 181, Research 350, Development or Engineering 122, Technical Management 262, General Management 76, Other 52.
Number of Personnel reporting to you (if a management category were checked):
Less than 10 80, 10–100 163, over 100 81.

TABLE 5.1b Discipline of Highest Degree

Discipline	Number of Responses	
Chemistry	43	95
Analytical Chemistry	1	
Physical Chemistry	43	
Inorganic Chemistry	2	
Organic and Polymer Chemistry	3	
Solid State Chemistry	1	
Polymer Processing	2	
Physics	129	153
Solid State Physics	14	
Applied Physics	4	
Chemical Physics	6	
Metallurgy	60	172
Mining, Geology, Geochemistry, Mineralogy	10	
Earth Sciences	1	
Physical Metallurgy	14	
Ceramics, Ceramics Engineering, Glass	44	
Metallurgical Engineering	31	
Materials Science	12	
Engineering	2	71
Mechanical Engineering	20	
Electrical, Electronic Engineering	12	
Aerospace	3	
Civil and Environmental Engineering	9	
Wood Technology	4	
Chemical Engineering	21	
Physiology	1	8
Industrial Management	3	
Political Science	1	
Zoology	1	
Economics	2	

Overall Importance of Materials Science and Engineering

The first page of the questionnaire asked for the "overall importance of Materials Science and Engineering" to each Area of Impact. The responses are summarized in Table 5.2a. The number of "1" (very high), "2" (high) responses etc. are indicated, as well as the corresponding rating on the 0–100 scale in the right-hand column.

TABLE 5.2a Overall Response

		Number of Responses					
Area of Impact		1	2	3	4	5	Rating
10	COMMUNICATIONS, COMPUTERS, AND CONTROL	298	185	68	14	2	84
20	CONSUMER GOODS	41	107	257	141	27	50
30	DEFENSE AND SPACE	366	165	41	3	2	89
40	ENERGY	329	187	53	4	4	1
50	ENVIRONMENTAL QUALITY	84	157	214	91	22	58
60	HEALTH SERVICES	54	165	227	91	30	55
70	HOUSING AND OTHER CONSTRUCTION	54	110	227	145	38	50
80	PRODUCTION EQUIPMENT	30	110	259	141	28	49
90	TRANSPORTATION EQUIPMENT	65	202	216	72	16	60

The responses can be grouped as:

TABLE 5.2b Overall Importance of Materials Science and Engineering to Each Area of Impact

Very Important	Defense and Space Energy Communications, Computers, and Control
Moderate	Transportation Equipment Environmental Quality Health Services
Low	Housing and Other Construction Consumer Goods Production Equipment

In Tables 5.3a through 5.3f, the responses of various sub-groups (selected using the personal data on the last page of the questionnaire) are presented. The number in parentheses above each category indicates the number of people in the group.

There are minor variations in these various Tables. These are indicated by "+" of "–" for a greater than 1s deviation from the mean, and by "++" or "—" for a greater than 2s deviation from the mean. Although few significant trends have been detected, some specific comments can be made. The responses from people with bachelors and masters degrees rate Communications lower than the larger group of Ph.D.'s and they also rate Production Equipment higher. This may reflect different interests of the two groups. In Table 5.3b, the Chemists are higher than average on Consumer Goods, Health Services, and low on Communications and Energy. The Physicists are high on Communications, low on Production and Transportation Equipment. Again these and other minor differences tend to reflect the interests of the group.

In Table 5.3c, the under-30 age group is small but the indicated differences from the other groups are statistically significant. The 30–39 age group rated Housing and Other Construction higher than average and gave a lower than average rating for Production Equipment. The 40–49 age group gave a low rating to Health Services, Housing and Other Construction and to Production Equipment. The over-50 age group gave a higher than average rating to Defense and Space, to Environmental Quality, to Production Equipment and to Transportation Equipment. Although there are significant deviations from the mean, no clearcut pattern emerges here.

TABLE 5.3a Assessment of the Overall Importance of Materials Science and Engineering to Each Area of Impact According to Highest Degree

Area of Impact		(62) Bachelors	(78) Masters	(379) Ph.D.
10	COMMUNICATIONS, COMPUTERS AND CONTROL	74—	78—	86+
20	CONSUMER GOODS	48	45–	51
30	DEFENSE AND SPACE	91	91	88
40	ENERGY	86	88	87
50	ENVIRONMENTAL QUALITY	61	59	59
60	HEALTH SERVICES	57	54	56
70	HOUSING AND OTHER CONSTRUCTION	50	50	50
80	PRODUCTION EQUIPMENT	53+	53+	47–
90	TRANSPORTATION EQUIPMENT	61	61	60

TABLE 5.3b Assessment of the Overall Importance of Materials Science and Engineering to Each Area of Impact According to Discipline of Highest Degree

Area of Impact		(95) Chemistry	(153) Physics	(172) Metallurgy	(71) Engineering	(8) Other
10	COMMUNICATIONS, COMPUTERS AND CONTROL	81–	91++	82	79–	78–
20	CONSUMER GOODS	54+	48	48	49	58
30	DEFENSE AND SPACE	90	88	90	91	89
40	ENERGY	83–	87	88	88	89
50	ENVIRONMENTAL QUALITY	59	58	60	57	67
60	HEALTH SERVICES	60+	55	52–	57	67+
70	HOUSING AND OTHER CONSTRUCTION	57++	43—	51	49	56
80	PRODUCTION EQUIPMENT	50	44—	51	51	44
90	TRANSPORTATION EQUIPMENT	62	56–	62	61	50

TABLE 5.3c Assessment of Overall Importance of Materials Science and Engineering to Each Area of Impact According to Age Bracket

Area of Impact		(5) <30	(74) 30–39	(214) 40–49	(262) >50
10	COMMUNICATIONS, COMPUTERS AND CONTROL	80	85	85	83
20	CONSUMER GOODS	45	52	49	50
30	DEFENSE AND SPACE	95	87	88	92+
40	ENERGY	75–	86	87	87
50	ENVIRONMENTAL QUALITY	75+	61	56	61+
60	HEALTH SERVICES	70+	56	56–	55
70	HOUSING AND OTHER CONSTRUCTION	55	55+	47–	51
80	PRODUCTION EQUIPMENT	65+	44–	46–	51+
90	TRANSPORTATION EQUIPMENT	50	61	59	62+

TABLE 5.3d Assessment of the Overall Importance of Materials Science and Engineering to Each Area of Impact According to Type of Institution

Area of Impact		(187) Academic	(120) Government	(215) Industrial	(16) Non-Profit	(17) Other
10	COMMUNICATIONS, COMPUTERS AND CONTROL	90++	80–	80—	86	85
20	CONSUMER GOODS	56++	45—	47–	58+	42–
30	DEFENSE AND SPACE	89	89	90	97+	83–
40	ENERGY	86	90+	86	84	82
50	ENVIRONMENTAL QUALITY	64++	56	57	56	52–
60	HEALTH SERVICES	63++	51—	52—	67+	40—
70	HOUSING AND OTHER CONSTRUCTION	52+	47–	50	56	48
80	PRODUCTION EQUIPMENT	52+	52+	46–	58+	38–
90	TRANSPORTATION EQUIPMENT	63+	61	58–	58	60

TABLE 5.3e Assessment of the Overall Importance of Materials Science and Engineering to Each Area of Impact According to Type of Activity

Area of Impact		(181) Teaching	(350) Research	(122) Development or Engineering	(262) Technical Management	(76) General Management	(52) Other
10	COMMUNICATIONS, COMPUTERS AND CONTROL	90++	87+	79—	83	78–	83
20	CONSUMER GOODS	55++	50	40—	48–	52	51
30	DEFENSE AND SPACE	89	88	89	91+	85–	87
40	ENERGY	87	86	86	89+	87	91+
50	ENVIRONMENTAL QUALITY	64++	59	60	59	67++	64+
60	HEALTH SERVICES	63++	58+	51—	54–	60+	56
70	HOUSING AND OTHER CONSTRUCTION	57++	50	49	50	57++	54+
80	PRODUCTION EQUIPMENT	53+	49	49	49	57++	47
90	TRANSPORTATION EQUIPMENT	63+	60	56–	63+	62	63

TABLE 5.3f Assessment of the Overall Importance of Materials Science and Engineering to Each Area of Impact According to Management Level

Area of Impact		(80) <10	(163) 10–100	(81) >100
10	COMMUNICATIONS, COMPUTERS AND CONTROL	83	82	81–
20	CONSUMER GOODS	47–	50	47–
30	DEFENSE AND SPACE	89	90	89
40	ENERGY	90+	87	88
50	ENVIRONMENTAL QUALITY	64+	59	58
60	HEALTH SERVICES	55	55	51–
70	HOUSING AND OTHER CONSTRUCTION	50	51	48
80	PRODUCTION EQUIPMENT	52+	48	49
90	TRANSPORTATION EQUIPMENT	62	62	62

The assessment broken down by type of institution in Table 5.3d shows that people in academic institutions gave higher ratings to a number of areas for the overall importance of Materials Science and Engineering than the rest of the community. The government and industrial laboratories are fairly consistent with each other and the non-profit group rates several areas higher than average and the people classified under "others" tend to give lower ratings than the average. But these latter two groups are small.

Table 5.3e shows the breakdown according to type of activity that the respondee is engaged in. Those engaged in teaching again gave significantly higher ratings than average and the ratings are very similar to the ratings given by the academic group in Table 5.3d (the two groups probably have most members in common). The people in development or engineering rate Communications, Consumer Goods, and Health Services low. The general management group are high on Environmental Quality, Housing and Production Equipment. The managers with between 10 and 100 people reporting to them gave ratings very close to the average ratings as shown in Table 5.3f.

The tendency of respondees to give a higher rating to those areas with which they are familiar or in which they are active than to other areas is further demonstrated in Table 5.4. In this table the responses from page 1 of the questionnaire are broken down according to the areas of impact with which the respondees are familiar. This was done in the following way. On page 2 of the questionnaire the respondees were asked to list areas and sub-areas in which they are knowledgeable or to which their experience relates. All of the respondees who indicated by a response on page 2 that they are familiar with, for example, Communications, Computers and Control were selected and the responses of this group to page 1 appear on the top line of Table 5.4. Those who indicated on page 2 a knowledge of or experience in Consumer Goods were grouped together and their responses appear on the second line. Of course, each respondee could indicate knowledge of, or experience in, up to five different sub-areas which might or might not be contained in the same area. His responses were counted in each of the groups in which he indicated knowledge and experience. Thus Table 5.4 gives a rating of how people who feel they are knowledgeable in a particular area, rate the importance of each of the areas of impact.

In each case, each group rated its own area approximately ten points higher than the average overall response (except for the three areas that already had very high scores). These ratings are found on the major diagonal of Table 5.4. The ratings of the other areas of impact by each group are not too different from the overall average. Each Area of Impact was given its highest rating by its own group, but the lower groups gave high ratings to areas other than their own. The right hand column in Table 5.4 is the average of the responses in each row and shows that each group of respondees gave fairly similar overall ratings. The bottom line in Table 5.4 is an average of each column in the table. These averages can be compared with Table 5.2a with which there is a high degree of consistency. The rankings given by each group to its own area, that is, the rating on the major diagonal of the Table, also give a rank ordering which is not dissimilar from the ranking shown in Table 5.2b. A few of the Areas of Impact change place but they can still be grouped into three categories shown there. We can conclude that although each group is

TABLE 5.4 Overall Importance of Materials Science and Engineering to Areas of Impact-Classification by Respondees Familiar with Area of Impact

Communications, Computers and Control	Consumer Goods	Defense and Space	Energy	Environmental Quality	Health Services	Housing and Other Construction	Production Equipment	Transportation Equipment	Average rating used by Group	
92	49	90	86	57	54	44	44	56	64	COMMUNICATIONS, COMPUTERS AND CONTROL
83	60	85	83	61	58	55	47	60	66	CONSUMER GOODS
81	45	92	85	53	52	46	45	60	62	DEFENSE AND SPACE
85	45	88	90	58	54	46	47	59	64	ENERGY
82	52	87	87	68	56	54	52	61	67	ENVIRONMENTAL QUALITY
83	49	87	85	58	69	50	46	58	65	HEALTH SERVICES
78	56	84	85	60	61	67	55	65	69	HOUSING AND OTHER CONSTRUCTION
76	48	89	85	56	53	50	61	59	64	PRODUCTION EQUIPMENT
81	49	89	86	55	53	52	49	69	65	TRANSPORTATION EQUIPMENT
82	50	88	86	58	57	52	50	61		Averaged Rating of Area of Impact

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The right hand column lists the groupings of people according to their chosen sub-areas of impact. The ratings of each group for all of the areas of impact are shown on a horizontal line.

enthusiastic about the importance of Materials Science and Engineering to the area with which they are familiar, the relative assessment of each group is nevertheless in line with the overall assessment.

The tendency of people familiar with or active in a particular area to rate highly the importance of Materials Science and Engineering to their own area runs throughout the responses in this report. This could be regarded merely as chauvinism on the part of the respondees who feel that their own areas are more important than others. But taken at face value, the more familiar the respondees are with a particular area the higher they rate the importance of Materials Science and Engineering to that area. From this point of view the rankings are a very healthy sign for Materials Science and Engineering.

The same trend runs through the responses for Priorities for Basic Research and for Applied Research and Engineering reported below. Here again, the correlation between the "familiarity" of a respondee with a particular area and the priority he feels should be accorded it for research may be regarded as merely self-serving. On the other hand, it could be regarded as indicating a fairly optimal situation in which interest and effort are being concentrated in the very areas to which high priority should be afforded. Indeed, both are true to some degree, since researchers tends to seek out the problems which they think are important within the areas of their backgrounds and interests, and also seek to improve their knowledge and expertise in areas which they believe to be important.

PRIORITIES FOR BASIC RESEARCH

The level of priority for basic research was assessed from responses on pages 3, 4 and 5 of the questionnaire (Appendix 5A). The level of priority for each of the Properties, Classes of Materials and Processes were requested. In addition, the familiarity of the respondee with each of these specialties was obtained. The responses in these two columns are summarized in Fig. 5.1, where the responses for the Priority for Basic Research are plotted vertically on a 1–100 scale and the familiarity rating is plotted horizontally on a 0–100 scale, although only the 10–80 part of this scale is shown on the horizontal axis. The responses for all three categories are shown. The Properties are shown as a "+", the Materials as a "o" and Processes as an "x". There is an obvious correlation between the familiarity of the respondees with a particular specialty and the Priority for Basic Research, which is shown by the general lower-left to upper-right trend of the data. As a result of this bias high priority should probably be accorded to categories which are on the upper envelope of the curve as well as to those which have a high absolute priority rating. Those on the lower envelope of the curve or with a low absolute rating should have less priority. On this basis the Properties that achieve highest priority are Mechanical and Acoustic Properties, Chemical Properties and Biological Properties; amongst the Materials, Ceramics, Glasses, Composites, Plastics and Prosthetic Materials rate highest; amongst the Processes Testing and Synthesis stand out. The Materials Asphalt, Wood and Concrete are at the bottom of the priority list for Basic Research.

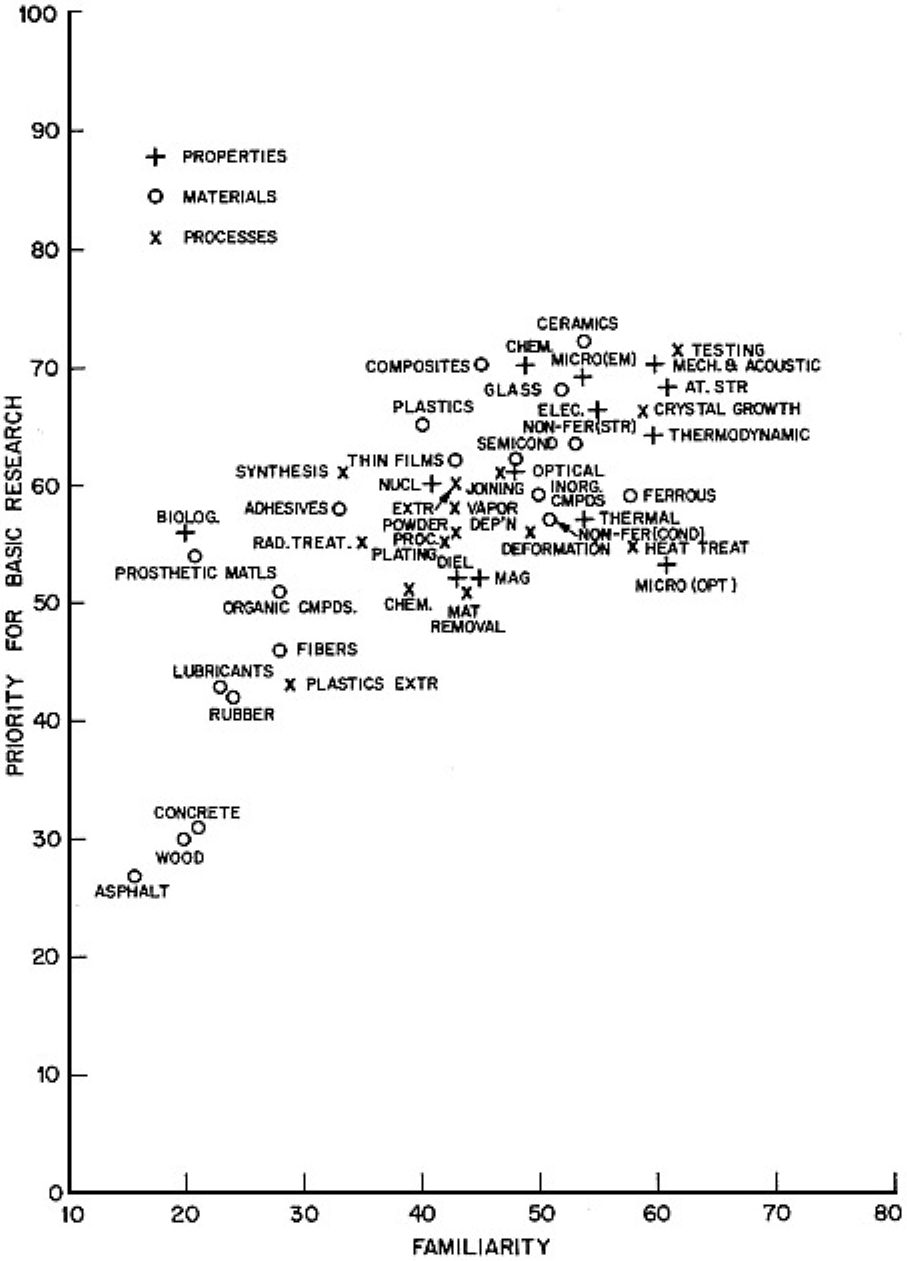

FIGURE 5.1 PRIORITY FOR BASIC RESEARCH

Priorities for Basic Research by Groups Based on Personal Data

The priorities for basic research accorded by each of the groups based on the personal data on the last page of the questionnaire were also collected and are presented in Tables 5.5a through 5.5f. The numbers in parentheses after each category are the number of respondees in each group. The ratings are shown for each class of materials, properties, and processes. The respondees were not asked to rate the priority for basic research in various disciplines.

The ratings in Table 5.5a are broken down according to highest degree of the respondee. The Ph.D. group was by far the largest and the ratings they gave to the various categories are, for that reason, fairly similar to the overall average. By and large the Ph.D. group tended to give higher ratings than the other two groups, especially to categories of more fundamental interest such as Atomic Structure, Microstructure (Electron Microscope Level), Electrical, Magnetic, Dielectric and Nuclear properties. Ph.D.'s also give higher ratings to Ceramics, Glasses, Composites, Thin Films and Prosthetic materials, as well as to Vapor Deposition, Radiation Treatment and Chemical Treatment. For the older and better established materials and processes the ratings tended to be more similar between the three groups. Table 5.5b gives the priority classified according to discipline of highest degree. Here the major groupings of Table 5.1b are presented along with ratings from the larger of the sub-groups. In these tables again one can see that the respondees rate the properties, materials and processes with which they are familiar more highly than others did. For example, the physicists and electrical engineers rate Electrical Properties much more highly than mechanical engineers. The physical chemists rate Prosthetic Materials much more highly than chemical engineers. The mining engineers rate Extraction as a very important process. Metallurgical and mechanical engineers are very high on Testing and Non-Destructive Testing but give Radiation Treatment a low rating.

Table 5.5c reports the priority for basic research according to the age of the respondee. There are differences amongst the various groups but the differences are not large so no coherent picture emerges from these data.

In Table 5.5d the priority for basic research according to the type of institution in which the respondee works is presented. Once again the members of the academic community tended, on average, to give higher ratings than the rest of the population. However many of the categories to which they gave high rating are the same areas to which the Ph.D.'s gave high ratings in Table 5.5a.

Table 5.5e presents the rating for priority for basic research classified by the type of activity. In this case the people involved in teaching consistently give higher ratings correlating well with academic group in Table 5.5d. Those doing development work give lower than average ratings to work on some of the more fundamental categories such as Optical, Electrical, Magnetic, Dielectric Properties and also to materials such as Semiconductors and Prosthetic Materials and to Radiation Treatment and Chemical Processing. These are the same categories to which the Ph.D. group gave higher than average ratings.

Table 5.5f shows the priority for basic research classified according to the level of management. Few significant differences emerge from these tables.

TABLE 5.5a Priority for Basic Research—Classified According to Highest Degree

Bachelors (62)	Masters (78)	Ph.D. (379)	
63	60	71	Atomic Structure
62	59	71	Microstructure (Electron Microscope Level)
45	50	54	Microstructure (Optical Microscope Level)
53	61	66	Thermodynamic
51	53	59	Thermal
64	72	70	Mechanical and Acoustic
41	50	65	Optical
50	52	71	Electrical
41	39	56	Magnetic
36	38	56	Dielectric
48	52	63	Nuclear
65	69	71	Chemical
50	49	58	Biological
67	66	74	Ceramics
59	53	72	Glasses and Amorphous Materials
50	46	66	Elemental and Compound Semiconductors
48	48	62	Inorganic, Non-Metallic Elements and Compounds
64	59	60	Ferrous Metals and Alloys
60	63	63	Non-Ferrous Structural Metals and Alloys
42	53	60	Non-Ferrous Conducting Metals and Alloys
68	61	65	Plastics
38	42	48	Fibers and Textiles
41	37	44	Rubbers
65	64	73	Composites
42	46	53	Organic and Organo-Metallic Compounds
54	45	67	Thin Films
53	61	59	Adhesives, Coatings, Finishes, Seals
40	44	44	Lubricants, Oils, Solvents, Cleansers
37	46	60	Prosthetic and Medical Materials
23	34	33	Plain and Reinforced Concrete
26	28	27	Asphaltic and Bituminous Materials
21	28	32	Wood and Paper
48	59	61	Extraction, Purification, Refining
53	53	63	Synthesis and Polymerization
54	59	68	Solidification and Crystal Growth
55	57	57	Metal Deformation and Processing
37	40	44	Plastics Extrusion and Molding
50	57	56	Heat Treatment
51	48	52	Material Removal
61	60	61	Joining
52	54	58	Powder Processing
47	45	61	Vapor and Electrodeposition, Epitaxy
42	40	60	Radiation Treatment
52	50	56	Plating and Coating
38	40	55	Chemical
76	72	71	Testing and Non-Destructive Testing

TABLE 5.5b Priority for Basic Research—Classified According to Discipline of Highest Degree

Chemistry (95)	Physical Chemistry (43)	Chemical Engineering (21)	Physics (153)	Solid State Physics (14)	Metallurgy/Ceramics (172)	Mining, Geology, Geochemistry, Mineralogy (10)	Physical Metallurgy (14)	Ceramics, Ceramic Engineering, Glass (44)	Metallurgical Engineering (31)	Materials Science (12)	Engineering (71)	Mechanical Engineering (20)	Electrical, Electronic Engineering (12)	Total	
65	72	57	72	65	70	70	77	75	70	58	65	59	88	68	Atomic Structure
67	71	55	68	68	72	70	79	73	70	65	63	55	72	69	Microstructure (Electron Microscope Level)
54	53	61	47	48	61	54	52	68	60	65	43	43	43	53	Microstructure (Optical Microscope Level)
59	58	60	68	77	67	70	58	68	67	55	53	50	59	64	Thermodynamic
57	55	61	62	66	54	60	52	58	54	42	50	41	72	57	Thermal
67	69	71	62	52	76	87	65	74	83	80	66	67	56	70	Mechanical and Acoustic
54	50	50	76	78	52	55	62	52	52	53	45	31	72	61	Optical
65	67	50	80	84	56	58	59	54	57	39	51	37	77	66	Electrical
50	46	36	63	66	49	55	52	49	52	28	31	26	50	52	Magnetic
49	48	36	65	69	44	55	47	47	36	39	36	25	65	52	Dielectric
57	60	50	65	71	59	50	56	54	62	65	41	44	46	60	Nuclear
73	77	80	64	70	76	63	70	77	77	71	65	64	78	70	Chemical
65	61	66	55	56	52	65	47	50	43	46	53	50	64	56	Biological
72	76	69	68	65	81	82	72	92	73	66	55	50	66	72	Ceramics
64	68	53	77	77	67	66	64	86	58	63	57	46	83	68	Glasses and Amorphous Materials
54	58	32	76	79	57	50	56	64	56	42	52	35	67	62	Elemental and Compound Semiconductors
57	58	50	67	70	57	68	52	63	45	42	41	30	53	59	Inorganic, Non-Metallic Elements and Compounds
60	56	65	55	65	69	70	59	65	77	55	50	57	37	59	Ferrous Metals and Alloys
64	62	75	57	56	70	62	63	60	81	61	54	65	35	63	Non-Ferrous Structural Metals and Alloys
53	58	41	63	72	59	50	50	63	61	56	37	34	40	57	Non-Ferrous Conducting Metals and Alloys
71	63	67	60	56	66	65	63	64	64	64	62	54	71	64	Plastics
53	49	50	41	35	47	50	32	46	52	50	38	34	32	46	Fibers and Textiles
49	45	40	39	35	44	43	37	41	52	32	36	41	28	42	Rubbers
74	73	69	66	60	74	79	67	67	78	83	66	68	46	70	Composites
48	46	44	61	65	45	50	40	45	41	39	43	35	42	51	Organic and Organo-Metallic Compounds
58	59	48	74	75	55	62	52	64	46	43	52	35	88	62	Thin Films
60	54	58	53	52	62	65	57	65	64	53	59	60	53	58	Adhesives, Coatings, Finishes, Seals
45	43	44	40	37	47	56	35	50	51	32	40	39	29	43	Lubricants, Oils, Solvents, Cleansers
59	69	26	55	45	56	65	52	56	47	50	42	32	64	54	Prosthetic and Medical Materials
32	30	30	25	20	38	66	25	38	36	35	33	33	16	31	Plain and Reinforced Concrete
28	23	26	21	20	31	37	17	34	32	17	25	25	16	27	Asphaltic and Bituminous Materials
35	31	38	24	27	31	43	31	31	31	17	28	16	25	30	Wood and Paper
64	63	69	57	68	64	89	55	70	58	43	39	23	66	60	Extraction, Purification, Refining
66	62	46	60	63	56	55	50	57	50	56	58	50	71	61	Synthesis and Polymerization
60	66	46	72	77	66	58	57	71	65	63	60	45	82	66	Solidification and Crystal Growth
59	60	59	48	50	66	50	66	52	73	50	47	58	39	56	Metal Deformation and Processing
48	50	34	39	38	45	60	38	39	46	39	41	45	28	42	Plastics Extrusion and Molding
56	51	50	50	63	64	60	63	65	66	63	38	41	37	55	Heat Treatment
52	51	44	47	50	58	54	40	54	63	42	41	44	53	51	Material Removal
61	62	51	51	52	70	66	69	65	79	64	59	62	59	61	Joining
56	54	50	49	63	69	54	60	80	63	56	43	48	53	56	Powder Processing
53	51	42	68	79	53	54	57	54	43	50	48	36	82	58	Vapor and Electrodeposition, Epitaxy
52	51	34	73	75	42	35	41	44	40	46	41	25	78	55	Radiation Treatment
54	50	53	54	68	57	45	55	52	63	50	48	48	62	55	Plating and Coating
47	45	34	60	63	45	50	36	52	35	37	45	30	80	51	Chemical
76	77	69	62	56	76	66	75	78	84	71	75	76	78	71	Testing and Non-Destructive Testing

TABLE 5.5c Priority for Basic Research–Classification by Age

(74)	(214)	(262)	
< 39	< 49	< 50	
64	68	69	Atomic Structure
67	69	69	Microstructure (Electron Microscope Level)
55	52	53	Microstructure (Optical Microscope Level)
65	65	63	Thermodynamic
59	56	57	Thermal
73	66	73	Mechanical and Acoustic
63	64	57	Optical
66	70	63	Electrical
46	55	52	Magnetic
51	56	48	Dielectric
60	59	59	Nuclear
75	67	72	Chemical
61	55	56	Biological
70	72	72	Ceramics
68	72	64	Glasses and Amorphous Materials
61	63	61	Elemental and Compound Semiconductors
54	60	58	Inorganic, Non-Metallic Elements and Compounds
60	55	63	Ferrous Metals and Alloys
62	58	67	Non-Ferrous Structural Metals and Alloys
59	55	58	Non-Ferrous Conducting Metals and Alloys
67	64	66	Plastics
46	46	46	Fibers and Textiles
45	42	43	Rubbers
75	70	70	Composites
49	54	49	Organic and Organo-Metallic Compounds
54	65	62	Thin Films
61	55	61	Adhesives, Coatings, Finishes, Seals
47	40	46	Lubricants, Oils, Solvents, Cleansers
56	56	53	Prosthetic and Medical Materials
34	29	33	Plain and Reinforced Concrete
33	24	27	Asphaltic and Bituminous Materials
31	29	32	Wood and Paper
55	57	63	Extraction, Purification, Refining
56	60	63	Synthesis and Polymerization
68	66	64	Solidification and Crystal Growth
58	51	60	Metal Deformation and Processing
49	41	42	Plastics Extrusion and Molding
58	54	56	Heat Treatment
52	49	53	Material Removal
65	57	63	Joining
60	54	59	Powder Processing
58	58	58	Vapor and Electrodeposition, Epitaxy
53	55	56	Radiation Treatment
58	53	56	Plating and Coating
50	53	48	Chemical
68	69	75	Testing and Non-Destructive Testing

TABLE 5.5d **Priority for Basic Research-Classification According to Type of Institution**

Academic (187)	Government (120)	Industrial (215)	Non-Profit (16)	Other (17)	
72	62	68	64	56	Atomic Structure
73	60	69	67	62	Microstructure (Electron Microscope Level)
56	45	54	61	50	Microstructure (Optical Microscope Level)
71	56	63	56	55	Thermodynamic
64	53	54	54	47	Thermal
72	71	68	71	67	Mechanical and Acoustic
66	52	61	63	60	Optical
76	58	63	63	56	Electrical
64	42	49	50	47	Magnetic
61	39	52	50	36	Dielectric
67	58	53	63	50	Nuclear
73	66	72	63	55	Chemical
64	49	53	65	52	Biological
75	65	73	70	66	Ceramics
75	57	67	70	68	Glasses and Amorphous Materials
67	50	63	59	65	Elemental and Compound Semiconductors
62	48	61	56	63	Inorganic, Non-Metallic Elements and Compounds
61	61	57	54	69	Ferrous Metals and Alloys
65	64	58	56	70	Non-Ferrous Structural Metals and Alloys
66	52	51	45	62	Non-Ferrous Conducting Metals and Alloys
67	61	66	55	75	Plastics
54	44	40	40	64	Fibers and Textiles
48	39	40	40	48	Rubbers
76	69	67	60	75	Composites
56	47	49	56	56	Organic and Organo-Metallic Compounds
68	55	62	52	67	Thin Films
61	55	59	38	75	Adhesives, Coatings, Finishes, Seals
46	48	45	36	46	Lubricants, Oils, Solvents, Cleansers
66	50	47	56	58	Prosthetic and Medical Materials
37	31	28	30	40	Plain and Reinforced Concrete
32	28	23	25	34	Asphaltic and Bituminous Materials
35	27	29	22	39	Wood and Paper
68	51	57	58	57	Extraction, Purification, Refining
63	57	61	52	67	Synthesis and Polymerization
70	58	66	63	70	Solidification and Crystal Growth
60	54	54	47	57	Metal Deformation and Processing
47	37	43	33	57	Plastics Extrusion and Molding
62	50	53	58	53	Heat Treatment
54	47	52	41	45	Material Removal
62	59	62	52	53	Joining
65	52	54	50	58	Powder Processing
61	50	59	58	46	Vapor and Electrodeposition, Epitaxy
60	50	52	63	50	Radiation Treatment
58	50	57	44	45	Plating and Coating
56	43	51	55	39	Chemical
70	74	71	75	57	Testing and Non-Destructive Testing

TABLE 5.5e Priority for Basic Research–Classified According to Type of Activity

Teaching (181)	Research (350)	Development (122)	Technical Management (262)	General Management (76)	Other (52)	
74	68	56	67	69	73	Atomic Structure
75	69	60	69	67	73	Microstructure (Electron Microscope Level)
57	54	48	55	50	58	Microstructure (Optical Microscope Level)
73	65	56	63	55	70	Thermodynamic
65	59	50	56	56	56	Thermal
73	69	67	72	66	75	Mechanical and Acoustic
66	64	48	62	59	63	Optical
77	71	51	65	67	64	Electrical
65	55	39	50	53	58	Magnetic
61	55	38	50	50	54	Dielectric
68	62	51	61	53	66	Nuclear
75	69	70	75	63	75	Chemical
65	67	49	56	51	64	Biological
77	72	71	72	72	75	Ceramics
76	70	62	65	70	71	Glasses and Amorphous Materials
67	64	50	61	67	58	Elemental and Compound Semiconductors
66	62	52	59	58	53	Inorganic, Non-Metallic Elements and Compounds
62	58	61	58	60	69	Ferrous Metals and Alloys
66	61	60	63	61	65	Non-Ferrous Structural Metals and Alloys
67	60	50	55	56	66	Non-Ferrous Conducting Metals and Alloys
68	63	65	65	67	64	Plastics
55	48	43	41	47	55	Fibers and Textiles
50	44	41	39	38	44	Rubbers
77	71	66	69	71	69	Composites
57	53	43	50	53	46	Organic and Organo-Metallic Compounds
70	65	54	60	65	56	Thin Films
63	57	58	59	58	56	Adhesives, Coatings, Finishes, Seals
48	42	41	43	43	46	Lubricants, Oils, Solvents, Cleansers
66	59	42	48	52	57	Prosthetic and Medical Materials
38	31	32	28	36	38	Plain and Reinforced Concrete
31	28	29	23	28	25	Asphaltic and Bituminous Materials
36	30	30	29	25	35	Wood and Paper
68	60	53	58	65	69	Extraction, Purification, Refining
64	62	53	59	61	62	Synthesis and Polymerization
71	69	56	65	66	62	Solidification and Crystal Growth
61	54	52	57	61	59	Metal Deformation and Processing
49	43	39	42	38	43	Plastics Extrusion and Molding
63	58	52	55	56	63	Heat Treatment
55	48	50	53	51	52	Material Removal
65	58	64	62	63	65	Joining
66	57	53	57	61	58	Powder Processing
62	60	47	57	64	46	Vapor and Electrodeposition, Epitaxy
61	58	37	55	55	49	Radiation Treatment
59	55	52	57	58	48	Plating and Coating
57	51	40	50	59	46	Chemical
72	70	71	74	77	66	Testing and Non-Destructive Testing

TABLE 5.5f Priority for Basic Research-Classified According to Level of Management

(80) < 10	(163) 10-100	(81) > 100	
65	67	71	Atomic Structure
64	69	68	Microstructure (Electron Microscope Level)
52	54	59	Microstructure (Optical Microscope Level)
60	62	57	Thermodynamic
53	55	55	Thermal
68	71	70	Mechanical and Acoustic
62	62	59	Optical
68	64	67	Electrical
52	51	48	Magnetic
56	48	46	Dielectric
64	59	60	Nuclear
72	75	69	Chemical
55	53	59	Biological
66	74	70	Ceramics
60	69	64	Glasses and Amorphous Materials
59	63	60	Elemental and Compound Semiconductors
55	59	57	Inorganic, Non-Metallic Elements and Compounds
62	60	55	Ferrous Metals and Alloys
66	63	61	Non-Ferrous Structural Metals and Alloys
56	56	55	Non-Ferrous Conducting Metals and Alloys
67	64	63	Plastics
41	43	46	Fibers and Textiles
39	41	37	Rubbers
68	69	70	Composites
54	46	56	Organic and Organo-Metallic Compounds
64	63	59	Thin Films
58	59	54	Adhesives, Coatings, Finishes, Seals
42	43	43	Lubricants, Oils, Solvents, Cleansers
47	49	49	Prosthetic and Medical Materials
31	30	29	Plain and Reinforced Concrete
23	24	24	Asphaltic and Bituminous Materials
33	27	27	Wood and Paper
60	57	66	Extraction, Purification, Refining
61	58	60	Synthesis and Polymerization
64	69	59	Solidification and Crystal Growth
56	59	56	Metal Deformation and Processing
40	41	41	Plastics Extrusion and Molding
55	57	49	Heat Treatment
52	52	49	Material Removal
66	63	57	Joining
56	60	52	Powder Processing
56	57	55	Vapor and Electrodeposition, Epitaxy
56	51	56	Radiation Treatment
60	54	53	Plating and Coating
48	51	54	Chemical
72	74	73	Testing and Non-Destructive Testing

Ratings of Priority for Basic Research by Experts in Each Specialty

The level of priority for basic research in each of the specialties of Properties, Classes of Materials and Processes are presented in Tables 5.6a, b and c as rated by experts in each category. The "experts" were selected as follows. In the questionnaire each respondee was asked to rate his familiarity with each of the specialties. In constructing Tables 5.6 the respondee who rated himself 2, that is, indicated that he had a very high familiarity with the particular specialty, was selected as an "expert" in that specialty. Respondees could of course rate themselves as experts in more than one specialty, but the few who rated themselves as very familiar with more than five specialties in one category of Properties, Materials, Processes or Disciplines were excluded.

The specialty for each group is shown on the right hand side of the page in Tables 5.6 and the number of people who rated themselves as very familiar with that specialty is indicated in the left hand column. The respondees were asked to rate their familiarity with each of the specialties under properties, classes of materials, processes and disciplines. However they were not asked to rate the priority that should be accorded to basic research in the disciplines so that the tables include ratings given by the four sets of experts but for only the three categories of Properties (5.6a), Materials (5.6b) and Processes (5.6c). These tables are similar to Table 5.4 in structure.

Each group of experts gave a high priority to basic research in their specialty. These ratings tended to be significantly higher than the average rating. For example, one of the highest numbers in the table is for basic research on Prosthetic Materials given by the experts in that area. This rating of 94 is considerably above the group average rating of 54, although Fig. 5.1 identifies this as an important area for basic research. The highest number in the table is the 100 priority rating given by the 8 experts in Organic and Organo-metallic Compounds for basic research on Joining.

Much detailed information can be derived from these tables, for example the 66 experts on Optical Properties give a high rating for basic research on Optical and Electrical Properties, they rate Semiconductors, Glasses and Thin Films as important materials for basic research (Table 5.6b) and Radiation Treatment (presumably ion implantation) and Crystal Growth as important processes for basic research (Table 5.6c). Similarly the reader can extract information about the properties, materials and processes which are viewed as important by each group of experts.

The diagonal elements of these three tables, that is, the rating by each group of experts of their own specialty, were used as part of the input to Tables 5.7, where an attempt is made to assess overall priorities for Basic Research.

TABLE 5.6a Level of Priority for Basic Research **Classified According to Classes of Materials** as Rated by Experts in Each Category

Number of Experts	Atomic Structure	Microstructure (Electron Microscope Level)	Microstructure (Optical Microscope Level)	Thermodynamic	Thermal	Mechanical and Acoustic	Optical	Electrical	Magnetic	Dielectric	Nuclear	Chemical	Biological	
96	83	79	57	70	61	70	63	71	58	57	69	71	56	Atomic Structure
56	75	79	62	69	57	73	68	67	53	52	53	67	55	Microstructure (Electron Microscope Level)
119	73	76	64	68	54	78	52	53	43	43	55	73	56	Microstructure (Optical Microscope Level)
87	79	76	58	80	59	74	58	67	54	55	69	78	69	Thermodynamic
64	73	68	49	68	69	66	61	71	55	52	65	62	56	Thermal
131	65	68	53	60	53	84	45	52	42	41	53	71	51	Mechanical and Acoustic
66	70	67	45	62	60	58	81	78	60	54	51	57	52	Optical
97	72	66	45	66	63	57	77	82	62	65	64	64	53	Electrical
52	68	70	48	65	57	59	72	75	67	64	82	63	51	Magnetic
41	72	72	53	58	61	62	69	74	56	73	58	62	51	Dielectric
37	75	68	50	58	57	75	69	72	52	49	84	78	49	Nuclear
68	63	64	53	60	53	67	49	59	44	42	53	82	61	Chemical
14	37	61	52	40	44	50	41	53	43	50	46	80	77	Biological
86	70	72	59	68	58	78	55	60	47	50	57	70	55	Ceramics
71	72	70	58	72	62	72	61	66	49	52	58	66	58	Glasses and Amorphous Materials
87	77	71	48	69	61	53	82	83	59	66	66	62	46	Elemental and Compound Semiconductors
62	76	68	45	67	64	65	70	77	57	58	66	60	50	Inorganic, Non-Metallic Elements and Compounds
145	69	70	56	62	55	77	52	62	54	45	62	73	55	Ferrous Metals and Alloys
110	68	71	58	64	53	80	51	60	52	41	59	75	34	Non-Ferrous Structural Metals and Alloys
68	73	75	55	69	60	71	63	76	60	56	68	72	58	Non-Ferrous Conducting Metals and Alloys
37	63	65	58	61	47	74	51	62	40	54	49	74	60	Plastics
18	64	73	60	63	55	75	55	67	40	67	57	82	71	Fibers and Textiles
20	67	66	64	66	45	76	50	64	42	57	50	75	67	Rubbers
36	63	69	54	65	48	63	38	45	31	34	49	73	42	Composites
8	71	82	71	64	54	71	75	62	58	41	67	83	50	Organic and Organo-Metallic Compounds
45	83	75	52	66	65	70	74	83	65	64	72	71	53	Thin Films
19	68	78	62	67	45	75	54	58	41	39	62	80	39	Adhesives, Coatings, Finishes, Seals
9	81	71	59	59	65	75	67	82	75	57	85	78	78	Lubricants, Oils, Solvents, Cleansers
10	63	80	61	55	58	61	50	63	66	55	58	72	86	Prosthetic and Medical Materials
19	60	58	45	61	63	81	42	39	41	33	46	68	58	Plain and Reinforced Concrete
7	65	60	60	45	45	70	31	40	25	30	55	75	65	Asphaltic and Bituminous Materials
11	54	65	39	37	39	57	35	45	33	42	30	78	60	Wood and Paper
55	72	70	58	68	63	66	62	70	55	54	60	71	59	Extraction, Purification, Refining
31	70	68	51	66	58	65	58	67	55	66	55	69	60	Synthesis and Polymerization
111	74	73	50	69	57	63	68	76	58	59	64	67	51	Solidification and Crystal Growth
79	69	70	53	58	49	77	53	55	50	40	63	75	58	Metal Deformation and Processing
20	60	66	54	63	60	77	60	67	45	65	56	76	61	Plastics Extrusion and Molding
105	72	75	59	67	55	77	52	60	50	47	61	75	56	Heat Treatment
28	69	75	56	63	60	83	65	67	51	52	64	72	66	Material Removal
45	62	71	50	50	53	80	42	56	37	50	51	80	50	Joining
48	71	76	61	72	62	79	53	56	46	47	54	74	54	Powder Processing
52	77	73	47	67	59	56	77	79	60	67	62	70	46	Vapor and Electrodeposition, Epitaxy
37	73	70	42	63	68	59	85	81	66	63	74	66	44	Radiation Treatment
27	63	69	59	56	60	70	60	65	53	47	59	80	57	Plating and Coating
27	72	76	45	55	62	55	78	82	60	66	60	66	53	Chemical
137	63	68	50	59	56	80	52	60	46	50	55	75	56	Testing and Non-Destructive Testing
30	66	68	57	71	58	73	47	58	51	44	48	73	61	Earth Sciences
16	56	68	47	37	50	65	52	61	52	50	56	68	63	Analytical Chemistry
63	74	70	54	61	57	72	62	71	49	52	60	70	60	Physical Chemistry
26	60	61	53	60	47	64	53	61	41	53	43	68	64	Organic and Polymer Chemistry
23	66	72	51	65	57	71	66	72	59	57	60	63	60	Inorganic Chemistry
56	68	67	45	67	62	65	73	77	64	58	55	68	59	Solid State Chemistry
149	73	69	48	66	62	62	77	62	61	63	63	63	53	Solid State Physics
76	71	75	61	71	63	80	61	64	50	52	59	72	57	Ceramics and Glass
16	64	75	64	64	44	72	55	55	51	53	46	66	60	Polymer Processing
27	61	61	55	68	55	72	50	64	48	83	59	83	59	Extractive Metallurgy
74	64	68	58	61	55	79	45	32	43	39	55	73	51	Metals and Inorganic Materials Processing
115	68	71	55	64	54	78	50	56	48	42	60	76	57	Physical Metallurgy
15	64	67	57	62	57	71	60	67	50	42	57	71	71	Chemical Engineering
25	55	56	44	51	40	67	35	44	30	34	50	68	59	Mechanical Engineering
31	72	68	51	63	62	65	65	74	53	63	53	66	51	Electronic Engineering
16	71	71	53	59	62	81	55	61	51	55	62	78	53	Aerospace Engineering
10	70	63	44	55	61	72	52	61	43	43	83	72	56	Nuclear Engineering
4	66	91	75	50	41	66	65	57	66	41	50	91	100	Bioengineering
14	60	68	56	54	58	68	41	47	43	53	50	64	67	Civil and Environmental Engineering

Table 5.6b Level of Priority for Basic Research Classified According to Classes of Properties as Rated by Experts in Each Category

Number of Experts	Ceramics	Glasses and Amorphous Materials	Elemental and Compound Semiconductors	Inorganic, Non-Metallic Elements and Compounds	Ferrous Metals and Alloys	Non-Ferrous Structural Metals and Alloys	Non-Ferrous Conducting Metals and Alloys	Plastics	Fibers and Textiles	Rubbers	Composites	Organic and Organo-Metallic Compounds	Thin Films	Adhesives, Coatings, Finishes, Seals	Lubricants, Oils, Solvents, Cleansers	Prosthetic and Medical Materials	Plain and Reinforced Concrete	Asphaltic and Bituminous Materials	Wood and Paper	
96	82	78	68	64	63	65	64	60	46	41	73	52	68	55	44	60	32	25	26	Atomic Structure
56	79	76	63	58	57	64	58	70	58	50	79	58	63	63	48	65	35	31	34	Microstructure (Electron Microscope Level)
119	76	67	57	54	65	67	55	69	50	49	74	50	55	64	47	59	33	30	36	Microstructure (Optical Microscope Level)
87	78	73	65	63	61	65	49	63	50	46	72	51	66	61	41	64	33	27	38	Thermodynamics
84	73	72	67	50	62	62	62	61	47	37	69	56	66	56	38	61	33	30	33	Thermal
131	67	58	48	52	65	69	49	63	46	45	75	46	48	60	42	50	34	25	29	Mechanical and Acoustic
66	67	76	79	70	53	51	60	58	40	36	56	58	74	52	34	51	20	22	21	Optical
97	66	77	78	66	51	54	62	58	38	35	62	62	76	50	37	50	21	19	22	Electrical
52	68	75	70	69	57	56	61	61	48	48	63	62	73	47	41	58	38	26	36	Magnetic
41	68	78	68	64	47	46	51	68	51	41	65	65	72	53	37	50	32	18	34	Dielectric
37	75	73	72	71	69	71	75	55	41	31	58	49	64	45	39	41	22	26	20	Nuclear
68	71	61	50	55	62	66	49	71	47	46	72	47	51	62	43	51	33	29	38	Chemical
14	50	45	35	45	47	61	50	87	73	65	75	54	67	77	52	47	45	40	59	Biological
86	88	78	61	61	60	60	55	60	47	37	72	47	61	62	43	61	36	25	31	Ceramics
71	83	85	65	57	52	50	53	63	49	41	71	49	61	61	43	61	34	25	34	Glasses and Amorphous Materials
87	66	76	84	68	50	50	59	54	34	32	62	56	75	48	35	48	19	16	22	Elemental and Compound Semiconductors
62	82	79	73	79	60	66	65	55	40	31	64	56	70	46	38	54	22	18	19	Inorganic, Non-Metallic Elements and Compounds
145	74	61	54	53	73	76	60	65	43	40	75	48	52	56	44	53	34	27	29	Ferrous Metals and Alloys
110	77	61	57	55	71	80	59	67	44	44	77	48	51	61	46	51	36	29	31	Non-Ferrous Structural Metals and Alloys
68	76	71	67	62	69	74	70	67	47	41	73	55	62	56	43	56	39	32	30	Non-Ferrous Conducting Metals and Alloys
37	56	62	45	53	45	53	42	87	65	61	60	53	61	66	42	60	37	28	40	Plastics
18	52	62	47	54	57	55	50	89	77	68	68	60	77	76	53	82	43	31	45	Fibers and Textiles
20	56	64	46	53	40	50	44	80	65	72	81	60	58	68	48	75	39	31	33	Rubbers
36	66	55	41	45	54	68	41	73	50	50	86	45	44	66	45	46	33	24	30	Composites
8	59	68	64	57	75	82	62	66	41	66	78	82	75	50	54	33	29	50	41	Organic and Organo-Metallic Compounds
45	74	75	74	62	57	60	62	66	45	41	73	60	83	58	41	50	25	21	20	Thin Films
19	67	65	48	50	55	61	48	82	53	45	76	50	57	76	50	50	44	28	26	Adhesives, Coatings, Finishes, Seals
9	84	71	67	30	75	81	64	75	60	50	78	65	63	65	78	75	39	42	37	Lubricants, Oils, Solvents, Cleansers
10	77	77	40	37	50	55	46	83	59	59	81	53	59	66	46	94	34	31	37	Prosthetic and Medical Materials
19	59	56	38	48	54	51	35	67	48	42	80	51	40	64	43	59	54	38	30	Plain and Reinforced Concrete
7	50	50	40	45	70	65	45	66	47	40	66	55	55	55	55	45	40	54	29	Asphaltic and Bituminous Materials
11	53	42	46	42	46	46	46	83	68	43	66	44	60	77	50	68	40	27	65	Wood and Paper
55	76	67	68	68	61	67	68	65	46	41	70	55	61	60	42	55	37	31	34	Extraction, Purification, Refining
31	69	69	62	68	51	55	50	82	60	63	85	56	70	66	50	65	36	30	38	Synthesis and Polymerization
111	76	76	70	65	54	59	56	60	44	38	68	51	67	51	37	54	29	21	27	Solidification and Crystal Growth
79	73	63	53	55	65	72	55	70	47	45	72	52	50	63	46	53	37	31	34	Metal Deformation and Processing
20	53	59	44	60	50	61	43	88	67	70	84	58	55	71	53	52	39	31	45	Plastics Extrusion and Molding
105	76	66	60	59	68	71	60	66	48	43	71	46	55	63	44	61	35	30	35	Heat Treatment
28	75	61	55	52	69	72	56	70	50	46	79	50	43	67	51	53	34	25	38	Material Removal
45	61	52	42	52	64	61	48	69	46	45	73	49	46	68	48	41	29	24	35	Joining
48	90	77	66	62	65	64	57	65	53	42	73	47	58	61	44	61	38	29	33	Powder Processing
52	71	74	76	60	46	50	62	60	35	32	69	52	77	52	36	52	23	21	20	Vapor and Electrodeposition, Epitaxy
37	69	77	62	70	55	60	68	58	39	33	62	63	75	48	32	47	24	20	21	Radiation Treatment
27	70	58	56	53	65	71	55	69	52	45	73	48	64	61	60	45	38	36	44	Plating and Coating
27	67	77	81	60	48	52	62	60	42	31	50	47	77	53	35	59	22	18	30	Chemical
137	70	62	55	57	60	61	52	69	49	46	73	53	59	64	47	55	37	26	33	Testing and Non-Destructive Testing
30	80	58	57	61	65	62	56	65	46	36	66	50	63	65	51	56	40	37	36	Earth Sciences
16	73	56	52	45	52	61	43	75	50	47	72	33	56	61	52	47	29	27	34	Analytical Chemistry
63	75	72	63	60	55	56	51	67	51	45	73	48	61	57	43	59	28	22	27	Physical Chemistry
26	61	56	47	50	44	46	44	90	69	68	86	54	57	72	47	66	32	26	35	Organic and Polymer Chemistry
23	78	76	62	54	52	56	48	65	34	26	67	31	68	53	35	60	25	20	23	Inorganic Chemistry
56	77	61	70	71	53	54	54	62	46	37	72	48	70	52	41	56	23	18	22	Solid State Chemistry
149	70	77	75	68	52	56	60	58	42	37	65	58	72	50	37	52	23	19	24	Solid State Physics
76	89	83	62	61	58	58	54	60	47	36	73	44	62	58	40	59	37	28	38	Ceramics and Glass
16	59	63	54	56	43	54	45	80	67	64	83	59	54	73	44	51	32	23	41	Polymer Processing
27	69	58	57	61	69	70	63	63	48	38	76	50	50	55	44	48	26	20	35	Extractive Metallurgy
74	73	60	52	51	72	72	56	62	43	42	75	43	47	58	42	43	31	25	27	Metals and Inorganic Materials Processing
115	76	63	53	51	71	74	59	62	43	42	72	44	55	61	46	53	31	25	29	Physical Metallurgy
15	72	55	28	43	71	75	53	59	53	43	56	40	53	56	53	18	37	37	43	Chemical Engineering
25	55	51	36	31	62	63	42	63	42	43	73	50	43	60	50	46	43	33	36	Mechanical Engineering
31	68	77	77	62	55	58	59	64	39	39	64	54	78	56	41	54	29	25	25	Electronic Engineering
16	66	66	58	51	64	66	51	80	50	50	85	55	65	71	61	50	25	13	29	Aerospace Engineering
10	80	65	57	67	69	66	68	37	37	28	56	42	60	46	35	55	17	25	31	Nuclear Engineering
4	83	83	33	50	33	41	33	75	50	50	83	41	50	83	41	91	25	25	33	Bioengineering
14	61	55	40	51	59	59	46	71	53	46	73	55	55	59	55	46	59	50	50	Civil and Environmental Engineering

TABLE 5.6c Level of Priority for Basic Research Classified According to Processes as Rated by Experts in Each Category

Number of Experts	Extraction, Purification, Refining	Synthesis and Polymerization	Solidification and Crystal Growth	Metal Deformation and Processing	Plastics Extrusion and Molding	Heat Treatment	Material Removal	Joining	Powder Processing	Vapor and Electrodeposition, Epitaxy	Radiation Treatment	Plating and Coating	Chemical	Testing and Non-Destructive Testing	
96	69	64	76	62	42	64	55	61	63	62	62	53	51	72	Atomic Structure
56	63	68	78	53	54	59	57	66	63	55	57	51	48	77	Microstructure (Electron Microscope Level)
119	63	63	67	66	50	65	58	65	64	50	49	53	44	60	Microstructure (Optical Microscope Level)
87	68	62	74	60	48	66	53	61	63	56	58	54	53	67	Thermodynamic
64	61	59	69	54	44	57	47	47	50	56	63	48	52	66	Thermal
131	50	56	61	61	42	56	52	67	56	45	41	50	36	79	Mechanical and Acoustic
66	57	62	70	44	39	50	43	44	42	64	71	51	61	60	Optical
97	59	59	71	46	36	50	48	47	49	69	73	53	65	64	Electrical
52	62	56	72	47	35	54	43	51	50	63	70	52	61	58	Magnetic
41	61	63	68	41	35	47	49	52	56	62	67	50	62	69	Dielectric
37	64	68	73	64	39	59	52	69	51	60	71	60	52	70	Nuclear
68	63	62	62	56	45	53	54	67	55	54	48	59	45	72	Chemical
14	59	81	42	46	42	42	43	61	43	42	50	62	56	64	Biological
86	64	61	69	52	39	66	55	62	70	59	53	54	51	77	Ceramics
71	67	69	69	45	40	67	51	57	65	57	58	50	55	76	Glasses and Amorphous Materials
87	57	59	81	44	32	47	45	46	47	75	76	52	66	59	Elemental and Compound Semiconductors
62	70	63	78	55	39	54	47	55	54	67	67	52	59	67	Inorganic, Non-Metallic Elements and Compounds
145	63	55	65	68	42	59	55	68	60	51	47	56	41	74	Ferrous Metals and Alloys
110	57	56	67	74	43	62	58	72	64	53	44	60	39	79	Non-Ferrous Structural Metals and Alloys
68	67	80	72	65	41	58	56	61	62	61	55	61	48	69	Non-Ferrous Conducting Metals and Alloys
37	46	73	57	52	60	50	48	64	47	44	48	56	46	70	Plastics
18	55	76	58	59	70	63	56	57	56	50	59	62	60	66	Fibers and Textiles
20	48	78	54	51	71	56	42	63	57	33	50	53	41	66	Rubbers
36	34	59	63	65	46	52	60	72	57	44	32	53	35	81	Composites
8	50	78	70	56	18	75	62	100	50	62	68	75	50	70	Organic and Organo-Metallic Compounds
45	70	63	75	59	46	52	52	57	51	75	70	60	66	79	Thin Films
19	51	71	67	53	53	53	55	82	52	58	53	57	51	85	Adhesives, Coatings, Finishes, Seals
9	82	64	62	75	58	71	67	65	75	75	50	60	54	85	Lubricants, Oils, Solvents, Cleansers
10	42	65	57	57	50	64	53	60	67	46	42	50	39	68	Prosthetic and Medical Materials
19	50	57	60	46	50	48	33	66	43	38	40	38	36	75	Plain and Reinforced Concrete
7	43	62	62	50	56	43	37	56	56	31	31	43	43	60	Asphaltic and Bituminous Materials
11	53	75	54	35	65	35	42	59	35	45	50	45	41	80	Wood and Paper
55	85	64	67	58	46	57	51	63	62	58	52	61	54	66	Extraction, Purification, Refining
31	63	83	65	56	55	56	50	64	57	61	59	59	55	73	Synthesis and Polymerization
111	65	59	79	55	39	56	50	58	56	67	63	52	57	69	Solidification and Crystal Growth
79	60	61	65	71	46	60	59	73	62	52	46	58	44	82	Metal Deformation and Processing
20	46	73	52	58	69	57	55	68	56	41	46	58	48	71	Plastics Extrusion and Molding
105	67	57	67	66	43	64	56	66	63	50	49	57	45	75	Heat Treatment
28	56	66	65	64	44	58	63	77	62	50	48	66	41	81	Material Removal
45	52	60	50	53	38	50	45	72	50	43	38	55	40	79	Joining
48	65	64	71	61	45	68	57	69	82	56	44	53	47	49	Powder Processing
52	58	61	76	46	36	48	49	55	53	77	73	55	63	68	Vapor and Electrodeposition, Epitaxy
37	55	68	75	47	36	49	43	52	49	71	85	56	70	65	Radiation Treatment
27	61	65	62	61	46	53	55	63	67	57	55	66	52	75	Plating and Coating
27	64	60	73	43	55	47	50	48	46	70	78	53	79	60	Chemical
137	54	64	59	55	46	54	51	66	54	52	52	56	50	83	Testing and Non-Destructive Testing
30	69	59	65	54	45	62	47	60	65	57	42	55	46	73	Earth Sciences
16	50	50	40	55	36	47	47	66	55	52	55	50	45	80	Analytical Chemistry
63	64	67	67	55	48	55	52	62	57	61	62	52	50	76	Physical Chemistry
26	52	82	54	52	59	47	43	63	45	44	54	57	50	72	Organic and Polymer Chemistry
23	63	64	64	39	26	52	41	50	53	63	55	50	51	72	Inorganic Chemistry
56	66	66	76	55	42	54	50	54	53	67	68	53	58	67	Solid State Chemistry
149	60	62	74	49	37	50	46	50	48	69	73	52	63	65	Solid State Physics
76	68	65	70	51	38	65	56	61	69	56	50	50	51	73	Ceramics and Glass
16	55	73	53	55	62	51	57	64	55	46	51	60	48	71	Polymer Processing
27	82	61	59	62	58	51	46	58	60	51	41	61	48	62	Extractive Metallurgy
74	62	53	62	65	40	61	57	65	65	43	36	55	35	76	Metals and Inorganic Materials Processing
115	60	53	63	70	42	61	56	71	65	80	42	60	40	77	Physical Metallurgy
15	77	46	40	56	31	46	31	62	56	31	28	43	37	65	Chemical Engineering
25	37	51	55	61	48	50	37	63	48	46	35	48	42	65	Mechanical Engineering
31	58	58	74	47	36	46	50	54	50	70	38	60	71	69	Electronic Engineering
16	51	66	62	71	46	58	59	73	60	59	48	59	50	80	Aerospace Engineering
10	62	42	58	58	25	56	50	56	50	46	46	42	43	69	Nuclear Engineering
4	50	58	58	50	50	58	58	75	83	41	33	50	33	50	Bioengineering
14	55	75	55	48	44	44	30	50	42	38	46	46	50	69	Civil and Environmental Engineering

Overall Priority for Basic Research

From the foregoing it is Evident that there are several ways in which priorities for basic research in various specialties can be assigned on the basis of the data obtained in this survey. An overall rating for each of these specialties was obtained by factoring together various of these methods. In Tables 5.7a, b and c the overall priorities are presented along with the ratings that were factored into the result. These ratings were presented as Table 17 in the Summary COSMAT Report.* Three ways of obtaining overall priority were used. The first of these was to divide the respondees into four groups according to the discipline of highest degree, Chemists, Physicists, Metallurgists (including Ceramists) and Engineers as indicated in Table 5.1b. The simple rank orders in which each of these groups place the Properties, Classes of Materials and Processes were obtained. The four disciplinary groups were then given equal weight for arriving at average rating numbers for the given specialty. These ratings were converted to the four symbol scale where *** designates very high priority, ** high priority, * moderate priority, and a blank indicates low priority. These ratings are shown in the first column on the right in the Tables 5.7.

The second method of obtaining a rating involved an attempt to correct for the degree of familiarity of the respondees with the topic. Priority/ Familiarity trend lines were established graphically for each specialty on a plot similar to Fig. 5.1. The order of the specialties were then determined as a trend line was swept through the plots. This was done for each of the four disciplines and the results of this rank ordering are shown on the left side of the Tables 5.7. Again the groups were given equal weight in determining average rank and order which is shown in the second column on the right side of Tables 5.7.

The third method of obtaining an overall priority rating was based on the responses of the experts in each specialty as shown in Table 5.6. As previously mentioned the experts were chosen by selecting those who indicated very high familiarity with the specialty. The rank ordering by these experts, taken from the diagonal elements of Tables 5.6, is shown in the third column on the right in Tables 5.7.

The relative priorities for basic research depended somewhat on the method of analysis, for example, among the processes, basic research in Radiation Treatment was rated low priority by the method uncorrected for familiarity, it was rated moderate priority corrected for familiarity and was rated high priority by the experts in Radiation Treatment. It was felt that particular significance should be attached to those cases in which the specialty was rated as very high priority both by the familiarity-corrected method and by the experts in that specialty. Such weighting is incorporated in the Overall Rating listed in the fourth column on the right of Tables 5.7.

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* Materials and Man's Needs, Summary Report of the Committee on the Survey of Materials Science and Engineering, National Academy of Sciences, 1974.

TABLE 5.7a Priorities for Basic Research in Materials (Properties)

(*** - very high priority; ** - high priority; * - moderate priority; blank - low priority)

Rank, Allowing for Familiarity								
Chemists	Physicists	Metal- lurgists	Engineers		Uncorrected for Familiarity	Corrected for Familiarity	Experts	Overall Rating
OUT OF 13				PROPERTIES				
6	7	7	1	Atomic Structure (Crystallography and Defects)	***	**	*	**
4	4	3	3	Microstructure (Electron Microscope Level)	***	**	*	**
13	13	13	12	Microstructure (Optical Microscope Level)				
12	8	9	5	Thermodynamic (Phase Equilibria, Change of State, etc.)	**	*		*
10	12	12	8	Thermal (Thermal Conductivity, Phonons, Diffusion, etc.)	*			
5	9	2	6	Mechanical & Acoustic (Strength,Creep,Fatigue,Damping,etc.)	***	**	***	***
9	4	6	9	Optical (Emission,Absorption,Luminescence,Excitation,etc.)	*	*	**	**
3	3	8	7	Electrical (Conduction,Electron Trans.,Ionic Cond., Thermoelectric,Injection,Carrier Phen.	**	**	**	**
8	11	10	13	Magnetic (Ferromagnetic Resonance,Paramagnetic,etc.)				
11	10	11	11	Dielectric (Ferroelectric,Breakdown,Loss,Piezoelectric,etc.)				
7	6	5	10	Nuclear+ (Radiation Damage,Absorption,Surface States, Catalysis)	*	*	**	**
2	2	1	2	Chemical & Electrochemical+ (Corrosion,Battery Phen., Oxidation,Flammability,etc.)	***	***	***	***
1	1	3	4	Biological (Toxicity,Biodegradability,etc.)	*	***	***	***

+Due to a typographical error in the original questionnaire, Nuclear and Surface Properties were entered as one item. However, respondees generally read it as Nuclear and included Surface Properties under Chemical and Electrochemical.

TABLE 5.7b Priorities for Basic Research in Materials (Materials)

(*** - very high priority; ** - high priority; * - moderate priority; blank - low priority)

Rank, Allowing for Familiarity								
Chemists	Physicists	Metal- lurgists	Engineers		Uncorrected for Familiarity	Corrected for Familiarity	Experts	Overall Rating
OUT OF 19				MATERIALS				
3	5	1	5	Ceramics	***	***	***	***
6	1	6	4	Glasses and Amorphous	***	***	***	***
7	8	7	8	Elemental and Compound Semiconductors	**	**	***	**
12	11	13	11	Inorganic, Non-Metallic Elements and Compounds	*	*	**	*
10	16	18	16	Ferrous Metals and Alloys	***		*	*
5	10	14	13	Non-Ferrous Structural Metals and Alloys	**	*	*	*
13	12	19	15	Non-Ferrous Conducting Metals and Alloys	*			
4	7	3	3	Plastics	**	***	***	***
11	14	11	14	Fibers and Textiles				
14	15	12	12	Rubbers				
1	2	2	1	Composites	***	***	***	***
16	6	10	9	Organic and Organo-Metallic Compounds		*	*	*
9	4	8	6	Thin Films	*	**	**	**
8	9	4	2	Adhesives, Coatings, Finishes, Seals	**	**	*	**
15	13	9	10	Lubricants, Oils, Solvents, Cleansers		*		
2	3	5	7	Prosthetic and Medical Supplies	*	***	***	***
17	17	15	17	Plain and Reinforced Concrete				
19	18	17	19	Asphaltic and Bituminous Materials				
18	19	16	18	Wood and Paper				

TABLE 5.7c Priorities for Basic Research in Materials (Processes)

(*** - very high priority; ** - high priority; * - moderate priority; blank - low priority)

Rank, Allowing for Familiarity OUT OF 14 Chemists	Physicists	Metallurgists	Engineers	PROCESSES	Uncorrected for Familiarity	Corrected for Familiarity	Experts	Overall Rating
2	4	5	8	Extraction, Purification, Refining	*	**	***	**
4	1	3	2	Synthesis and Polymerization	**	***	**	**
8	5	9	3	Solidification and Crystal Growth	***	*	**	**
6	11	12	12	Metal Deformation and Processing	*			
13	12	7	10	Plastics Extrusion and Molding				
11	14	14	14	Heat Treatment				
10	13	13	13	Material Removal (Machinging, Electrochemical, Grinding, etc.)				
5	9	2	5	Joining (Welding, Soldering, Brazing, Adhesive, Bonding, etc.)	**	**	***	**
3	10	4	7	Powder Processing	*	*	**	*
9	3	10	4	Vapor and Electro-Deposition, Epitaxy	*	*	**	*
7	2	8	9	Radiation Treatment (Ion Implantation, Electron Beam, UV, etc.)		*	***	**
12	8	6	11	Plating and Coating	*			
14	6	11	6	Chemical (Doping, Photo-Processing, Etching, etc.)			**	
1	7	1	1	Testing and Non-Destructive Testing	***	***	***	***

Comments on Priority for Basic Research

In addition to the numerical responses a space was provided for the respondees to state the nature of the Basic Research they felt was needed in each category. These were brief one or two line descriptions, often a single phrase which would fit into the space provided. These responses have been collected and are presented on the following pages. Three stars have been assigned to items on which many people commented, two stars to items on which a number of people commented, and one star to comments made by one or a few people. The number in parentheses is the number of comments which were made in that specialty.

The categories which received most comments were those which are indicated in Fig. 5.1 to be given the highest priority for basic research. Among the properties these are Biological Properties and Chemical, Electrochemical and Surface Properties. Under Biological Properties biodegradibility, biocompatibility and toxicity were the most important sub-categories. Under Chemical, Electrochemical and Surface Properties corrosion and catalysis stood out. The materials which were selected for most comment were Biological Materials, Ceramics, Composites and Glasses and Amorphous Materials. The Ceramics were highly rated for research on their mechanical properties. In the Composites a better understanding of the basic properties of composite materials was emphasized. The transport properties and electrical properties of Glasses and Amorphous Materials were emphasized and better understanding of the degradation mechanisms in Plastics is recommended for high priority for basic research. The processes which received the largest number of comments were Polymer Synthesis and Testing and Non-Destructive Testing. The highest priority was given to improve methods for non-destructive flaw detection. The area of Testing and Non-Destructive Testing received high priority not only for basic research but generally in all the areas of Applied Research. A ubiquitous theme throughout these comments was the relationship between structure and properties, and the need for obtaining a better fundamental understanding of structure-property relationships in various materials and of their dependence on various processes.

The specialties rated as low-priority areas for basic research are of two general types. Some are areas which have been heavily studied in the past, leading to diminishing returns for such research today. Examples are Ferrous Metals and Alloys and Non-Ferrous Conducting Metals and Alloys. Others are areas which have never been subjected to intensive basic research, such as Concrete, Asphalt and Wood. In these cases our fundamental understanding may not yet be advanced to the point where research opportunities are recognizable, even by experts in the field.

Atomic Structure (150)

***Structure-property relationships: relation of structure to mechanical and physical properties; transport properties; texture; grain boundaries

***Relationship of point defects, especially to electrical properties

***Relationship of dislocations and stacking faults to mechanical properties

**Role of impurities

**Surfaces and surface structure; surface states

**Superconductivity effects of crystal structure and defects

**Corrosion and environmental protection; role of defects and impurities

*Catalysis

*Understanding chemical bonding

*Void nucleation and radiation damage in reactors

*Structure-property relationship in specific materials: high temperature ceramics, solid state displays, glasses, polymers, Al alloys, Ni alloys etc.

*Defect formation during crystal growth

Microstructure (Electron Microscope Level) (137)

***Defect-mechanical properties relationships; microstructure-property relationship; dislocation motion; fracture

**Morphologies: polymers, ceramics

**Failure mechanisms in electronic devices; deterioration of thin film devices; film characterization; corrosion

**Surface studies, interface phenomena, adsorption, grain boundaries, segregation

**Structure of precipitates; radiation damage induced voids; defects in electronic materials

*Biochemistry; tissue attachment and interface areas

*Flux pinning in superconductors

*Improvement of EM techniques

*High voltage electron microscopy; higher resolution; computer imaging methods

Microstructure (Optical Microscope Level) (108)

***Microstructure-property relationships; multiphase structures; effects of heat treatment; morphology; grain boundaries
*Fracture studies
*Quantitative metallography
*Polymer morphologies

Thermodynamic (116)

***Phase equilibria; phase stability; phase diagrams; alloy systems; gas solubilities; uranium compounds; borides; nitrides; silicides; transition metal alloys
***Kinetics of phase transformations; dynamics; crystal growth processes
***Control of microstructure; phase distributions
**Development of new materials; feasibility studies
**Equations of state; cooperative processes; irreversible thermodynamics; thermodynamic stability; solution theory
*Superconductivity and phase stability
*Stability of glasses and amorphous materials, glass-ceramics
*Corrosion resistance

Thermal (72)

***Thermal conductivity data: multicomponent systems; composites; high temperature; high pressure; amorphous materials; polymers; ceramics; semiconductors; insulators
**Phonon studies; electron-phonon interactions; liquid He II
**Improved thermal properties; catalysts; high temperature service; refractories; insulators
*Stability in service; phase stability

Mechanical and Acoustic (150)

***Fatigue; understanding mechanisms of fatigue; developing methods to eliminate fatigue; developing materials with improved fatigue resistance

***Fracture; nature of fracture; brittle fracture; fracture mechanics; crack propagation

***Creep: understanding mechanisms; viscoelasticity

***Environmental effects; stress corrosion; corrosion fatigue; durability; radiation fields; corrosive media; liquid metal corrosion

***Study of fundamental structure-property relations; origin of strength; strengthening mechanisms; multiphase systems

***Dislocation dynamics; point defect-dislocation interactions

***Improved mechanical properties of structural materials; alloys, metals and non-metals; ceramics; polymers; insulating materials; biomaterials; steels; high temperature materials; radiation resistant materials

***Nondestructive testing: new methods; flaw detection; for creep; for fatigue

**Composites: failure mode; strength; fatigue; computer design methods

**Acoustic damping

*More data on and better characterization of new materials

*Polymers: high impact polymers; fatigue; yield strength; impact strength; strain rate sensitivity

*Laser windows

*Ceramics: defect interactions; strength; impact resistance; acoustic properties

*Adhesion

Optical (74)

***Optical transmission, absorption and scattering mechanisms; role of impurities; absorption at high optical levels
**Lasers: new materials; new systems
**Relation of structure to optical properties: defects, develop optical methods as tools for structure studies
**Nonlinear optics
**Magneto-optics
*Optical properties of semiconductors; nonradiative recombination
*Solar cells
*Luminescence and phosphors
*Improved laser windows
*Photoemission
*Optical switching
*UV degradation
*Properties of liquid crystals

Electrical (117)

***Superconductivity; higher temperature superconductors; high current superconductors; new superconductors; room temperature superconductivity

***Transport mechanisms; scattering phenomena; electron-hole interactions; ionic mobility; ionic conductivity mechanisms in solids; metal-insulator transition; transport in molecular materials; electron tunneling; electron-electron, electron-phonon interactions; high pressure effects; high magnetic field low temperature conductivity

**Electrical properties of amorphous materials; carrier phenomena; transport; solid state physics of amorphous materials; liquids; amorphous semiconductors

**Correlation of electrical properties with structure and chemical properties; structure and carrier lifetime; impurity and vacancy concentrations; tailoring electrical properties

**Solar energy conversion; solar cells

**High performance conductors

**Interfaces; charge trapping; surface states; tunneling; dielectric-metal interface; nature of transport across a junction; contacts; surface effects in thin films; interface states in heterojunction III–V’s

*Radiation resistance semiconductors

*Electrical properties in biological materials; biopolymers

*Solid state electrolytes; ionic conductivity in solids

*Electro-optic compounds

*Liquid dielectrics

*Electronic properties of alloys

*Electro-chemical processes

*Electro-luminescence

*Photoconductivity

*Thermoelectricity; direct conversion of heat to electricity

*Conductivity in composites; in oxides

Magnetic (60)

***Magnetic domains; defect interactions; domain wall motion; correlation with structure; basic studies of magnetic damping; radiation damage

***New magnetic materials; magnetic properties of composites; development of rare-earth magnets; ferroelectric fluids; chalcogenides; ceramic metal and ceramic-organic composites; small particle magnets; ultra-thin film alloys; magnetic semiconductors

**Magnetic bubbles; relation of properties of bubbles to growth conditions and parameters

**Improved understanding of magnetic materials; spin-spin and spin-lattice interactions; ferrimagnetism and antiferromagnetism; physics of anisotropy in ferromagnets; relation of magnetism to superconductivity; magnetic semiconductors

**NMR and ESR of proteins and protein-ion complexes; biopolymers; biological materials

*Magnetic phase transitions; high pressure transitions

*Magneto-optical effects

*Surface waves

Dielectric (51)

***Dielectric breakdown: mechanisms; at low temperature and high field streng strength; at grain boundaries; relation to structure; in SiO_2, in $A1_2O_3$; in composites
**Environment; effects of moisture; effects of extreme temperatures; lightning
**Ferroelectricity; domain dynamics; domain phenomena
*Electriets
*High temperature dielectrics; high frequency dielectris; high pressure dielectrics
*Measurements of high frequency losses; loss mechanisms in polymers
*Effects of composition, processing and microstructure on dielectric properties
*Acoustic waves
*Surface waves
*Relation to optical properties; electron-optic properties

Nuclear (58)

***Radiation damage: kinetics of swelling; void nucleation and growth; defect physics; damage mechanisms; effect on properties; swelling of fuels; stability at high temperature and neutron flux; radiation damage at high temperatures in alloys and insulators; of fuel elements; of semiconductors; of superconductors; of structural materials; of u/Pu compounds
**Ion implantation
**Nuclear shielding; handling and disposal of nuclear materials; safety and reliability; monitoring of nuclear materials
*Effect of radiation on DNA; effect of low level irradiation on people
*Radiation for corrosion inhibition; radiation methods for hardening of alloys

Chemical, Electrochemical and Surface Properties (152)

***Corrosion, stress corrosion, and oxidation: fundamental understanding of mechanisms of; role of surface states, defects and impurities. Corrosion in: aqueous systems, hot gases, thin films; Corrosion at interfaces with biological media; Corrosion of iron and steel, concrete, refractories; Stress corrosion of Al, Ti, iron and steel; hydrogen embrittlement; of ceramics, glasses, and thin films; Oxidation at high temperature; role of impurities; of light metals

***Catalysis: fundamental understanding of mechanism of: role of surface structure, impurities, states and charges; effect of free radicals wavelength sensitive free radicals; nature of adsorption mechanisms

**Surfaces: physics and chemistry of; surfaces of noncrystalline solids

**Flammability: fundamental mechanisms of burning; role of additives, rates of burning, smoke generation, fume toxicity; kinetics of reactions at interfaces

**Chemical stability; decomposition and degradation mechanisms

**Electrochemical reactions: fundamental understanding of; electrode reactions, electrode materials, electrolytic corrosion of metals, joints; effect of surface structure; ionic conduction in battery separations; solid state electrolytes; fuel cell mechanisms; mechanisms of galvanic corrosion and protection

*Chemistry of fundamental, nonequilibrium processes; simplified methods for studying these

*Metal hydriding mechanisms

*Mechanism of adherence between metals and oxides

*Reaction mechanisms in molten salt chemistry; mass transport in liquid metals

*Effect of chemicals, food, liquids on woven articles

Biological (86)

***Biodegradability: fundamental mechanisms of interaction between materials (plastics, metals, glass, etc.) and the environment; role of fungi, enzymes, hyphae development; bacterial corrosion mechanisms; mechanisms useful for garbage disposal, recycling

***Biocompatibility: long-term chemical behavior and biological effects of materials and their breakdown products; cell and protein interactivities at surfaces; interaction between materials (metals, plastics, etc.) and biological materials (blood, cell tissue, etc.); rejection mechanisms, immunological response to implants and resorptable ceramics; better understanding of biological materials so that they can be replaced with synthetics

***Toxicity; of materials, organic compounds, colors, dyes, etc.; mechanisms of heavy metal incorporation into biological compounds; effect of trace elements and pollutants on humans; ecological impact of materials; sound standards for pollution and toxicity control

**Membranes: mechanisms, structure of; synthetic membranes

*Surface structure and chemical absorption; conformation of proteins

*Mechanisms of brain function, memory, signalling and energy transfer and relation to artificial intelligence

*What was wrong with nerve gas?

Ceramics (111)

***Mechanical properties: tensile and impact strength, toughness, effects of flaws; ductility, elastic and plastic deformation: thermal shock resistance; failure mechanisms; high-temperature properties; creep; effects of grain boundaries and microstructure

**Impurity effects on physical properties: on diffusion, thermal conductivity, electrical and ionic conductivity; on magnetic and optical properties

*Effect of Non-Stoichiometry on mechanical, chemical and transport properties; control of stoichiometry and defect structure to achieve desired physical properties

*Interfaces: metal-ceramic, fracture at.; surface wear

*Physical properties of basic oxides etc., e.g. BeO, UC_2, UO_2, UN

*Effect of microstructure on dielectric and magnetic pros.

*Factors controlling chemical reactivity, grain boundary chemistry, sintering

*Exploration for new ceramics: transparent ceramics, cermets, ductile ceramics, high compressive strength; high-temperature corrosion resistant, electro-optic ceramics

*Characterization

Glasses and Amorphous Materials (122)

***Transport properties and relation to structure particularly electrical: electrical effects at phase transitions; switching mechanisms; high electric field effects; electronic energy state distributions; phonon spectra and transport, surface dates, effect of high pressure

**Mechanical properties; ductility, elasticity and flexibility, strength and fracture, effects of defects, acoustic loss mechanisms, creep, sheer

**Phase separation; devitrification, spinodal decomposition, nature of glass transition, nucleation and crystal growth, role of impurities and surface nucleation in devitrification

*Relation of electronic properties to short range order structure

*Defect effects; on optical, magnetic and transport properties

*Surfaces; ion exchange treatments, corrosion mechanisms, diffusion

*Rheology of glasses

*Exploration for new glass systems; amorphous superconductors, chalcogenide glasses, glassy polymers; glasses with high dielectric strength, glassy carbons and relation of their structures to processing, glasses with low optical loss, ductile and tough glasses, rare earth glasses

*Electronic structure and transport in organic polymers

*Radiation damage; effect on mechanical and optical properties

*Structural characterization

*Structure and molecular dynamics

*Relation of transport in glasses to transport in liquids

*Optical absorption spectrum; impurity spectra

*Studies of basic oxide components of glasses—impurity effects, etc.

*Effect of transition to glassy state on magnetic properties

Elemental and Compound Semiconductors (84)

***Defect studies; control and elimination of crystal defects; defect properties; defects in compound semiconductors; structure-property relationships; chemical and physical purity; materials preparation; crystal growth; relation between preparation and properties; vacancy-impurity interactions; electrical, magnetic, and optical properties and their relation to defects and impurities; ion implantation

**Surface and interface states; surface and interface physics; surface and interface properties; junction physics

**Electronic band structure; chemical bonding; relation to ionicity

**Compound semiconductors; tailoring of properties; alloys; III–V compounds; ternary systems; new materials

**Solar cells; solar conversion; direct energy conversion

**Optical properties; light emitting diodes; photoconductors; large bandgap semiconductors; optical transitions

**Improved basic understanding; for prediction of new properties; for development of new materials; electronic and magnetic properties; nonlinear properties; phonon structure

*High temperature semiconductors; small bandgap semiconductors; piezoelectric semiconductors; varistors; glasses

Inorganic, Non-Metallic Elements and Compounds (68)

***Electronic properties: relationship between electronic and structural properties; electronic properties of unusual compounds; at high pressure; conductor-insulator transitions; electrical breakdown; ionic conductivity; superionic conductors; superconductivity; dielectric properties; solid state electrolytes

**Optical properties; magneto-optical materials; influence of defects on optical properties; optical properties of halides; luminescence; laser hosts

**Mechanical properties; high strength, high stiffness fibers; effect of impurities on boron fibers; light weight protective armour; structural weaknesses and failure; acoustic-vibration properties; materials for optical grinding; finishes; bearings

**Crystal chemistry; ultra high temperature chemistry; relation between structure and ionicity; relation of structure to electronegativity; chemical bonding; high oxidation states

*Magnetic properties; relation to defects; transparent ferromagnets; new magnetic compounds

*Characterization; properties, processing; single crystals

*Organo-silicon chemistry

*Liquid crystals

*Improved catalysts; fuel cells

*Noncombustible polymers

*High melting, oxidation resistant compounds

*Radiation response

Ferrous Metals and Alloys (60)

***Mechanical properties; impact resistance; high strength at high temperature; improved strength; high toughness; high toughness with high strength; reduction of low temperature embrittlement; fracture toughness; creep

**Structure and properties; fracture vs microstructure; structure of alloys; microstructure studies; morphology of graphite in cast iron; precipitates to improve strength; texture development

**Fracture studies; crack propagation; fatigue resistance; service failure

**Corrosion resistance; improved oxidation resistance; corrosion resistance for gas turbine elements; chloride stress corrosion; protective coatings

*Dislocation dynamics; defect-dislocation interactions

*Prediction of physical properties

*Non-destructive testing; degradation

*Adsorbed gases

*Hydrogen embrittlement

*Magnetic properties

*Powder metallurgy

*Casting methods; casting of large sections

Non-Ferrous Structural Metals and Alloys (73)

***High temperature, high strength alloys; high temperature properties; high temperature alloys

***Corrosion studies; corrosion resistance; corrosion mechanisms; stress corrosion; environmental effects; oxidation resistant refractory metals

***Fracture properties; brittleness; fracture resistance; fracture mechanisms; fracture toughness; fatigue; nature of fatigue; fatigue resistance

***Structure property relationships; relation of mechanical properties to microstructure and composition; static and dynamic properties; dislocation dynamics

**Radiation resistance; high temperature and high flux; radiation induced creep

**Improved strength to weight ratio

*Mechanical properties characterization

*Aluminum and aluminum alloys

*Titanium and titanium alloys

*Nickel and nickel based alloys

*Alloy substitution

*Beryllium alloys; zirconium alloys

*Nickel catalysts

Non-Ferrous Conducting Metals and Alloys (43)

***Superconductivity; high temperature superconductors; origins of high temperature superconductivity

**High strength conductors; resistivity-strength relationships

*Relationship of electronic to structural properties

*Thin film conductors

*Electrical contacts

*Degradation

Plastics (90)

***Structure-property relationships; relation of properties to structure, bonding, side-chains, cross-linking; role of thermal and mechanical history in determining structure and properties; better characterization of microstructure; effect of high pressure; of glassy polymers

***Durability: at higher temperatures; fundamental understanding of degradation mechanisms; stability; loss of elasticity; aging

***Mechanical properties; improved strength; impact properties; fracture; high temperature, strength; toughness; viscoelasticity; rheology

**Polymer surfaces; bonding mechanisms in high temperature plastics; composites

**Biodegradable plastics; recyclable plastics

*Nature and function of flame retardants

*Radiation resistance

*Better property data

Fibers and Textiles (30)

***Flame retardants; flammability; fire resistance

**Mechanical properties; less expensive high modulus fibers; increased wet strength; increased bend strength; relation between structure and properties

**Stability; structural deterioration; high temperature stability; degradation

*Biological applications

*Surface properties; surface finish

*Glass fibers; reinforcing materials

Rubbers (17)

***Chemical properties; high temperature stability; corrosion protection; sealants; oil resistance; oxidation stability

**Characterization of structure; fundamental properties; phase transitions in rubber

*Thermoplastic rubbers

*Wear

*Fibers for reinforcement

Composites (117)

***Interface bonding properties: fundamental understanding of behavior of fiber/matrix interface behavior; characterization on microelasticity scale; compatibility of reinforcement and matrix; mechanical strength; stress transfer between fiber and matrix; static and dynamic loading effects; adhesive forces; electronic structure at interfaces; bonding control; interface chemistry; effects of molecular variables on adhesives; relation between interfacial reactions and properties; thermal stability

**Mechanical properties: structural aspects; strength; ductility; toughness; brittle fracture; rheological properties; directional properties; dispersion hardening

*Durability: prediction of service life

*Exploration for new composites: organic composites; polymeric alloys— phase equilibria; oriented composites; new combinations of precipitates, fibers, platelets with organic or metal matrix; cements; high temperature oxidation resistant composites; multi-phase composites; boron and graphite fibers

*Radiation effects

*Nonstructural properties: thermal, electrical, optical; flammability, degradibility

*Characterization and analysis methods

*Joining methods

Organic and Organo-Metallic Compounds (45)

***Electronic structure; energy transfer mechanisms; high T_C superconductors; photochemical changes; optical properties; electron transport; semiconductors; photoconductors; luminescence; one-dimensional conductors

**Liquid crystals
*Finishes
*Precipitation of dyes in electric field
*Catalysts; surface phenomena
*Physiological activity

Thin Films (76)

***Preparation of thin films; control of crystallinity; defect structure of thin films; epitaxial growth mechanisms; elimination of grain boundaries; factors affecting crystal size and alignment; film-substrate interactions; molecular beam epitaxy

**Properties of ultra-thin films
**Membranes; biological membranes; transport of ions in membranes
*Electronic properties; magneto-electric properties
*Optical properties
*Difference between bulk and thin film properties; unique phase transitions in thin film geometry
*Transport in thin films; diffusion barriers
*Surface effects; interface with substrate; surface states
*Coatings; surface films to retard corrosion
*Electrodes; thin electrodes for fuel cell use
*Defects in bubble materials
*Catalysis
*Non-destructive evaluation
*Superconductivity studies; Josephson tunnel devices

Adhesives, Coatings, Finishes, Seals (56)

***Protective coatings; reliability; durability; corrosion; erosion; environmental sensitivity; protection against oxidation; aging characteristics; flame retardant

**Surface phenomena; surface chemistry; surface reactivity; surface finish

**Improved understanding of adhesion mechanisms; better characterization; nature of substrate-matrix interactions; cohesive reactions

**Improved adhesives for dissimilar materials; high temperature adhesives; higher strength adhesives

**Adhesion to live tissue

Lubricants, Oils, Solvents, Cleansers (22)

***High temperature lubricants; low temperature lubricants

***Long life lubricants; performance; stability; resistance to polymerization

**Pollution; toxicity; reusability

*Surface interactions

Prosthetic and Medical Materials (54)

***Biocompatibility: materials with physical and chemical properties matching adjacent hard and soft tissue. Surface effects: adsorption of blood, nature of surface mechanism of interface of materials with cells and proteins; correlation between in vivo and in vitro behavior; electrical interactions with body fluids; biorejection chemistry; durability

**New biomaterials; specific membranes; block polymers with ionic domains for controlled transport of long-term drugs; biological adhesives; fluoropolymers; glassy carbon

*Physical properties of implant materials

Plain and Reinforced Concrete (26)

***Mechanical properties; structure-property relationships; higher strength to weight ratio; greater ductility; failure mechanisms; improved wear; better toughness
**Concrete based on cements and aggregates utilizing solid wastes; plastic filled concrete
*Chemistry of Portland cement
*Weather resistance
*Characterization and testing methods

Asphaltic and Bituminous Materials (11)

**Improved asphalts, less slippery, less susceptible to temperature and oxidation

Wood and Paper (20)

**Improved properties; more uniformity; improved bending; improved wet strength
*Microstructure-property relationships in cellulose materials
*Fireproofing

Extraction, Purification, Refining (85)

***Ultra high purities; new and improved analytical methods for trace impurity analysis; removal of low level impurities; trace elements in steel; high purity glasses and ceramics; high purity oxides; high purity SiC; purity of superconducting materials
**Processing of low grade ores, more efficient extraction methods; low energy extraction methods
**Minimize environmental degradation; air and water pollution; recycling wastes; closed loop extraction; better use of by-products
*Seawater extraction
*High temperature vapor phase systems

Synthesis and Polymerization (70)

**High performance, high temperature plastics; strengthening and stabilizing processes; inducement and control of cross-linking

*Synthesis of macromolecules, high-density polymers free from non-biocompatible initiators, catalysis, promoters; low energy consuming processes

*Recycling of polymers; self-disintegrating plastics; photodecomposable, etc.

*Ultra-fine particle processing; polymerization at high pressure, high temperature, room temperature curing polymers

*Thermodynamics and kinetics of crystal growth processes

*Better ways of characterizing polymers

*Relation between synthesis and mechanical properties

*Photoeffects in polymers; photopolymerization, photosynthesis and photochemical changes

Solidification and Crystal Growth (97)

***Basic mechanisms of growth; kinetics of crystal growth; physics of melting; effect of trace elements on crystal growth; nucleation

**New materials; improved materials; new properties

**Ceramics; control of microstructure; heat treatable ceramics; melt forming of ceramics; grain growth control; sintering

**Polymers; potting compounds; high temperature polymers; controlled structure; controlled morphology; room temperature curing

**Single crystal preparation; growth defects; characterization

**High purity crystals; controlled purity crystals; zone refining; properties of pure materials

**Semiconductor crystals; epitaxy substrates; compound semiconductors; growth of heterojunctions

**Directional solidification of eutectics; control of eutectic structure

*Improved optical quality, nonlinear optical compounds; photo-optic materials

*Segregation in ingots; microsegregation and macrosegregation

*Control of microstructure in castings; effect of solidification on structure and properties; large ingot design

*High pressure growth

*Growth in zero gravity

Metal Deformation and Processing(48)

***Relationship between processing and properties: improved tensile strength; role of defects; physical characterization; effects on properties; effects of thermal mechanical history; role of dislocations; impurity aggregates; effects of hot and cold forming; grain boundaries at large deformation; formability; necking stability; strain hardening

**Improved forming for high strength alloys; improved deep drawing; aluminum deep drawing; powder preforms; laser machining

**Metal response to loading at high strain rate; high pressure deformation

*High temperature alloys

*New superplastic materials

*Improved fatigue life

*Fracture; failure mechanisms

Plastics Extrusion and Molding (7)

**Relationship between processing, structure and physical properties; orientation due to various extrusion methods; control of orientation

*Flexibility and durability

*Corrosion resistance

Heat Treatment (48)

***Effects of annealing on polymers

***Effects of thermal processing on microstructure; precipitation; texture; defect structures; effects of interrupted quenching; heat treatment of high strength alloys; high temperature kinetics

**Effects of magnetic field annealing; high pressure annealing; radiation effects; combined mechanical/thermal annealing

*Heat treatment to improve resistance to stress corrosion cracking; fatigue

*Semiconductors

*Superconductors

*Graded microstructures and properties

*Thermal mechanical aging

*Ferrous precipitation hardening

*Sintering, surface properties

*Isothermal transformations near critical points

Material Removal (29)

***New approaches; electrochemical machining; laser machining; faster, cheaper techniques; water, jet cutting. Machining of hard materials, superalloys, ceramics

*Surface structure; surface finish; surface phenomena

*Ultra fine etching

Joining (68)

***Resistance to vibration, abrasion; residual stresses; corrosion resistance; high temperature adhesives; bond strength; compatibility; new techniques; faster processing

***Interfacial phenomena; control of structure in weld zone; stress distributions in joints; fundamentals of adhesion; mechanism of joining; interfaces; surface chemistry and physics; properties of joints; compatibility; fundamental studies of adhesive bonding

**Plasma welding; vacuum hazing of aluminum; welding molybdenum

*Non-destructive testing methods; failure mechanisms

*Joining of composites

Powder Processing (48)

***Role of organic additives; interfaces in sintered bodies; effects of firing shrinkage; UHV sintering; pressure sintering; agglomeration

***Basic studies of sintering; pore removal; microstructure characterization; sintering kinetics; role of defects; purity effects; surface effects; interfaces in sintered bodies; role of organic additives; firing shrinkage; pressure sintering; UHV sintering

***Powder processing, mixing of powders; characterization of powders; particle size distributions; properties of extra fine powders; compaction; statistical properties of pressed powders; mechanics of particulate materials

**Physical properties; mechanical properties; directional strength; structure-property relationships

*Aluminum alloy powders; superalloy powder metallurgy

*Respirable dust characterization

*Superconductors

*Micro-quenched powders, spark sintering

Vapor and Electrodeposition, Epitaxy (44)

***Control of vapor deposition; chemical vapor deposition; molecular beam epitaxy; low temperature processes; purity; defect structure; elimination of grain boundaries; thin film properties

***Kinetics and thermodynamics of growth; surface phenomena; heat treatment; surface properties; surface structure studies; role of substrate in epitaxy; adhesion stresses; nucleation

***Amorphous films; semiconductor films; superconducting films; optical films; electrode materials; ceramics

*Oxidation resistant coatings; improved coatings

*High strength fibers

*Pyrocarbon technology

Radiation Treatment (54)

***Effects of irradiation; radiation damage; study of defects produced by irradiation; effects on semiconductors; effect on amorphous metals; channeling effects; creation of non-equilibrium phases

***Ion implantation; doping in semiconductors; to tailor electrical properties; to tailor-make solids; to reduce electron traps causing UV degradation.

**Polymers: improved cross-linking; polymerization; room temperature curing of polymers; UV and e-beam cross-linking polymers

*Production of stable ionic species in liquid electrolytes

*Effects on long term properties

Plating and Coating (39)

***Chemistry of metallic coatings on ceramics; electroless plating; uniformity of coatings; defects in coatings; basic parameters of plating and coating; surface reactions; adhesion; interfaces; surface properties

***Weather resistance and degradability; corrosion resistance; durability; coating to minimize stress corrosion; high temperature coatings; oxidation, sulphidation resistant coatings

**Coating of refractory metal composites

*Hydrogen embrittlement resulting from plating

*Controlled permeability coatings

*Deposition of magnetic alloys

*Cathode deposition phenomena in recharging spent fuel cells

*Plating of superconductors to enhance properties

*Cobalt free ground coat enamels

*Optical coatings

Chemical (35)

***Effects of dopants; solubility of impurities; defect structure; doping of semiconductors; dopants for compound semiconductors; improved metallization for semiconductors; control of doping and diffusion

**Microprocessing; photoprocessing; photochemical reactions

*Mechanisms of reactions; thermodynamics

*Battery phenomena

*Structure, properties, deformation and failure of complex materials

*Surface chemistry; surface chemistry and physics

*Corrosion of reactor materials; corrosion, oxidation; stress corrosion; preservation of wood

*Flammability; fire retardants

Testing and Non-Destructive Testing (123)

***Flaw detection: techniques for giving geometric description and location of flaws; crystallinity; texture, potential fracture, creep, crack propagation, fatigue; strength, joint integrity, ductility, etc.

**Techniques for automatic monitoring of manufacturing processes; automated simultaneous checking of several parameters

**Techniques for predicting performance and service life; accelerated aging testing; service environment testing; in-service indicators of incipient failure

**Exploitation of new physical phenomena and insights from solid state physics concerning interaction of radiation with matter: high temperature testing; acoustical and surface acoustic wave techniques, X-rays, holography, spectroscopy, sources of stress wave emission, infra-red and microwave properties, lasers, seismic resistivity; eddy currents, NMR and ESR

**Techniques for testing various materials; biomaterials in vitro and in vivo, dental evaluations; nuclear, structural irradiated materials; ceramics; electronic and other active materials; plastics; composites; consumer products; for surfaces, surface layers, interface reactions at molecular level; joints and welds

*Trace impurity detection and analysis in electronic and optical materials

APPLIED RESEARCH

The priorities for Applied Research depend on the area of application. In the questionnaire nine Areas of Impact were identified. In each of these Areas, several sub-areas were identified as listed in Table 5.8. Each respondee was asked to select up to five areas or sub-areas of application with which he was familiar. A rating was requested for the priority for Applied Research and Engineering which should be assigned to a variety of Properties, Materials, Processes and Academic Disciplines as related to each sub-area selected. Thus each respondee could confine his comments and priorities for Applied Research and Engineering to areas with which he was familiar. The number of responses which were made in each area and sub-area are indicated in Table 5.8.

The priorities for Applied Research derived from the responses are presented in summary form in Tables 5.9. The priorities are presented on a four-symbol scale with *** being very high priority, ** being high priority, * being moderate priority and a blank indicating low priority. The data presented in this table are also presented as numerical ratings in the sections dealing with each area of applied research.

Tables 5.10 present a rank ordering of the priorities for Applied Research and Engineering for the various areas and sub-areas of impact. In these tables the ratings given by the respondees have been corrected for familiarity by establishing a trend line on plots such as Fig. 5.2 and sweeping a trend line through the data to obtain rank ordering. This method is similar to that used to obtain the rank ordering for Basic Research (corrected for familiarity) presented in Tables 5.7. Thus in Table 5.10a the properties which should receive highest priority for applied research relating to Communications, Computers and Control are first, Electrical Properties; second, Dielectric Properties; third, Microstructure (Electron Microscope Level); fourth, Optical Properties; and so on.

Several specialties stand out in both the tables and the comments as having high priority almost across-the-board: Chemical Properties, for example, are rated as a high priority area for basic research and as well as for several impact areas. From the comments it is clear this assessment is related to a wide variety of chemical properties, including the pervading problems of corrosion and oxidation and the limitations they set on materials applications. Mechanical Properties, also receive high priority, as stronger and tougher materials are needed in nearly all fields of technology.

Of the Materials classes, Plastics received the highest overall priority rating, reflecting the still rapidly-growing use of these materials in a wide range of applications. The ratings also indicate the broad importance of Composite Materials, Non-Ferrous Structural Metals and Alloys, Ceramics and Adhesives, Coatings, Finishes and Seals. Under Processes, Testing and Non-Destructive Testing was of the most widespread priority, with Joining, Polymer Synthesis and Plastics Extrusion and Molding also rated of importance in many areas.

Although the above specialties received the broadest priority ratings, in particular areas of impact other specialties were rated of equal or greater importance. Biological Properties, for example, received high priority in the Environmental and Health areas. Semiconductors, Glasses, Prosthetic Materials and Lubricants were rated high for specific impact areas, as were the processes of Vapor Deposition and Chemical Processing.

Furthermore, the impact areas themselves are very broad, and some specialties rated very high in particular sub-areas do not appear in the figures because they were not of high priority for the area as a whole. For example, Electrical Properties were rated high priority in the sub-areas Batteries and Fuel Cells, Direct Conversion and Electrical Transmission and Distribution. However, since they were accorded low priority for Nuclear Reactors, Thermonuclear Fusion and Turbines and Generators, they were only of moderate priority for the overall area of Energy. High priority specialties for specific sub-areas can be determined from the tables and comments which are presented below.

TABLE 5.8 Sub-Areas of Impact and Responses Received

Code Number	Area or Sub-Area	Number of Responses
10	COMMUNICATIONS, COMPUTERS AND CONTROL	31
11	Commercial Radio and TV Equipment	10
12	Computers	66
13	Electronic Components	144
14	Equipment for Guidance and Control of Transportation	8
15	Teaching Equipment	14
16	Telephone and Data Networks and Equipment	41
Total 10 314		
20	CONSUMER GOODS	10
21	Apparel and Textiles	20
22	Furniture	6
23	Household Appliances—Electronic (TV, radio, hi-fi, etc.)	23
24	Household Appliances—Non-Electronic (refrigerators, ranges, airconditioners, vacuum cleaners, etc.)	19
25	Leisure and Sports Equipment	4
26	Packaging and Containers	34
27	Printing and Photography	25
Total 20 141		
30	DEFENSE AND SPACE	39
31	Military Aircraft	81
32	Missiles	38
33	Naval Vessels	25
34	Ordnance and Weapons	38
35	Radar and Military Communications	46
36	Spacecraft	54
37	Undersea Equipment	35
Total 30 356		
40	ENERGY	35
41	Batteries and Fuel Cells	100
42	Direct Conversion	62
43	Electric Transmission and Distribution	64
44	Fuel Transmission and Distribution	9
45	Nuclear Reactors	92
46	Thermonuclear Fusion	54
47	Turbines and Generators	66
		Total 40 482

Code Number	Area or Sub-Area	Number of Responses
50	ENVIRONMENTAL QUALITY	28
51	Mining and Raw Materials Extraction	65
52	Pollution	83
53	Recycling and Solid Waste Disposal	94
54	Reliability, Safety, Maintainability	25
55	Substitution Opportunities	19
56	Working Conditions	10
Total 50 324		
60	HEALTH SERVICES	14
61	Artificial Organs	39
62	Medical Electronics	13
63	Medical Equipment (including dental)	10
64	Prosthetic Devices (including dental)	64
Total 60 140		
70	HOUSING AND OTHER CONSTRUCTION	21
71	Construction Machinery	1
72	Highways, Bridges, Airports, etc.	19
73	Individual and Multiple Unit Dwellings	44
74	Industrial and Commercial Structures	12
75	Mobile Homes	13
76	Plumbing, Heating, Electrical, etc.	20
Total 70 130		
80	PRODUCTION EQUIPMENT	6
81	Farm and Construction Machinery	10
82	Industrial Drives, Motors and Control	9
83	Industrial Instrumentation	15
84	Machine Tools	22
85	Process Equipment	43
Total 80 105		
90	TRANSPORTATION EQUIPMENT	23
91	Aircraft	48
92	Automotive	75
93	Guided Ground Transportation (rail, non-rail)	30
94	Water	4
Total 90 180		
		GRAND TOTAL 2172

TABLE 5.9a Priorities for Applied Research -- Properties of Materials

Atomic Structure	Microstructure (Electron Microscope Level)	Microstructure (Optical Microscope Level)	Thermodynamic	Thermal	Mechanical and Acoustic	Optical	Electrical	Magnetic	Dielectric	Nuclear	Chemical	Biological	
***	**	*	*	*		***	***	**	**				COMMUNICATIONS, COMPUTERS AND CONTROL
***	**	*	*	*		**	***	**	**				Computers
***	***	*	*	*		**	***	*	**	*	*		Electronic Components
***	**	**	*	*	*	***	***	*	***		*		Telephone and Data Networks Equipment
*	*	*	*	*	*	*	*				*		CONSUMER GOODS
*	**	*	*	*	**						***	*	Apparel and Textiles
**	*	*	*	*	*	***	***	*	**				Household Appliances - Electronic
*	**	*	**	*	***						**	**	Packaging and Containers
*	**	**				***	***		*		*		Printing and Photography
*	**	**	*	*	***						*		DEFENSE AND SPACE
*	***	**	*	*	***						**		Military Aircraft
*	**	*	**	*	***					*	*		Missiles
	*	*			***						*		Naval Vessels
*	**	**	*	*	***	*				*	*		Ordnance and Weapons
**	*	*	*	*	*	***	***	*	**	*			Radar and Military Communications
*	**	**	*	**	***					*	*		Spacecraft
*	*	*			***						***		Undersea Equipment
**	**	*	**	**	**		*			*	***		ENERGY
**	*	*	**	*			***		*		***		Batteries and Fuel Cells
**	*	*	**	***	*	**	***		*	*	**		Direct Conversion
**	**		**	**	*		***	*	**				Electric Transmission and Distributors
***	***	**	**	**	***					***	***		Nuclear Reactors
***	***	*	*	**	***		*	*		***	**		Thermonuclear Fusion
*	***	*	**	*	***						***		Turbines and Generators
		*	*								**	*	ENVIRONMENTAL QUALITY
		*	**		*						**		Mining and Raw Materials Extraction
		*		*						*	***	*	Pollution
			*								**	**	Recycling and Solid Waste Disposal
*	**	**	*	*	***		*				***	*	Reliability, Safety, Maintainability
*	**	**	*		**						***	***	HEALTH SERVICES
	**	*	*		**		*				***	***	Artificial Organs
*	**	**	*		***						***	***	Prosthetic Devices
				*	***						**		HOUSING AND OTHER CONSTRUCTION
		*		*	***						**	*	Individual and Multiple Unit Dwellings
				*	**						*		Plumbing, Heating, Electrical, etc.
	*	*	*		**						*		PRODUCTION EQUIPMENT
*	**	**	*	*	**								Machine Tools
*	*	*	*	*	***						**		Process Equipment
*	*	*	*	*	***						**		TRANSPORTATION EQUIPMENT
*	**	**	*	*	***						**		Aircraft
*	*	**	*	*	***						***		Automotive
	*		*	*	***		*	*			*		Guided Ground Transportation

TABLE 5.9b Priorities for Applied Research -- Classes of Materials

Ceramics	Glasses and Amorphous Materials	Elemental and Compound Semiconductors	Inorganic, Non-Metallic Elements and Compounds	Ferrous Metals and Alloys	Non-Ferrous Structural Metals and Alloys	Non-Ferrous Conducting Metals and Alloys	Plastics	Fibers and Textiles	Rubbers	Composites	Organic and Organo-Metallic Compounds	Thin Films	Adhesives, Finishes, Coatings, Seals	Lubricants, Oils, Solvents, Cleansers	Prosthetic and Medical Materials	Plain and Reinforced Concrete	Asphaltic and Bituminous Materials	Wood and Paper	
*	**	***	**			*						***							COMMUNICATIONS, COMPUTERS AND CONTROL
*	**	***	*			*					*	***							Computers
**	***	***	**			*						***							Electronic Components
*	***	***	**			*	*					***							Telephone and Data Networks Equipment
	*						**	*		*	*	*	**						CONSUMER GOODS
							***	***	***	**	*		***	*				*	Apparel and Textiles
*	**	***	**				*			*	*	**							Household Appliances - Electronic
*	**						***	*		*			**					*	Packaging and Containers
	*	*	**				*				**	**	*						Printing and Photography
*	*			*	**		*			**			*						DEFENSE AND SPACE
*				*	***		*			***			**						Military Aircraft
*				*	**		*			***			*						Missiles
				*	**					*			*						Naval Vessels
*	*			*	**		*			**			*						Ordnance and Weapons
*	*	***	**									**							Radar and Military Communications
**	*			*			*	*		***			*						Spacecraft
*	*			***	***	*	*			**			*						Undersea Equipment
**			*	*	*	*													ENERGY
**	*	*	**			*													Batteries and Fuel Cells
**	*	*	*			*						**							Direct Conversion
*	*					***						*							Electric Transmission and Distributors
**				***	***														Nuclear Reactors
**	*		*	*	***	**													Thermonuclear Fusion
***				**	***	*				**									Turbines and Generators
*	*		*	*	*		*												ENVIRONMENTAL QUALITY
*			*	*	*														Mining and Raw Materials Extraction
*	*		*				*												Pollution
*	*		*	*	*	*	**		*	*								*	Recycling and Solid Waste Disposal
**	**	*		**	**	*	**	*	*	***		*	**						Reliability, Safety, Maintainability
*	*				*		***	*	*	**			*	***					HEALTH SERVICES
*	*				*		***	**	**	**		*	**		***				Artificial Organs
**	*				**		***	*		**			*		***				Prosthetic Devices
*	*			*	*		**	*		**			**			*	*	*	HOUSING AND OTHER CONSTRUCTION
*	*				*		***	*	*	**			***			*	*	*	Individual and Multiple Unit Dwellings
				**	*		*												Plumbing, Heating, Electrical, etc.
*				**	**														PRODUCTION EQUIPMENT
*				***	*														Machine Tools
*				***	*								*						Process Equipment
				**	**		**		*	**			*	*					TRANSPORTATION EQUIPMENT
				**	***		**			***			**	*					Aircraft
*	*			**	**		**	*	*	**			**	*					Automotive
				*	**	**	*			*									Guided Ground Transportation

TABLE 5.9c Priorities for Applied Research -- Processes

Extraction, Purification, Refining	Synthesis and Polymerization	Solidification and Crystal Growth	Metal Deformation and Processing	Plastics Extrusion and Molding	Heat Treatment	Material Removal	Joining	Powder Processing	Vapor and Electrodeposition, Epitaxy	Radiation Treatment	Plating and Coating	Chemical	Testing and Non-Destructive Testing	
*		***				*	*		***	**	*	**	**	COMMUNICATIONS, COMPUTERS AND CONTROL
		***							***	**	*	**	*	Computers
*		***			*	*	*		***	***	*	***	**	Electronic Components
*		**			*		*		**	*	*	**	**	Telephone and Data Networks and Equipment
	*			*			*				*		*	CONSUMER GOODS
	***			**			*						*	Apparel and Textiles
*	*	**		*			*		**	*	*	*	*	Household Appliances - Electronic
	*			*	*								**	Packaging and Containers
	**	*							*	*	*	***	*	Printing and Photography
		*	*		*	*	**	*			*		***	DEFENSE AND SPACE
		*	***		**	**	***	*			*		***	Military Aircraft
			*		*	*	**				*		***	Missiles
			*		*		**						*	Naval Vessels
		*	**		**	*	*	*			*		*	Ordnance and Weapons
		***					*		**	**		*	**	Radar and Military Communications
			**		*	*	***	*			*		***	Spacecraft
			**		*	*	***				*		**	Undersea Equipment
		*	*		*		*	*			*		**	ENERGY
		*						*	*		*	*	*	Batteries and Fuel Cells
*		**					*		**	*	*	*	*	Direct Conversion
*		*	*		*				*		*		*	Electric Transmission and Distributors
			**		**		**	*					***	Nuclear Reactors
			*		*		*			*	*		***	Thermonuclear Fusion
		**	***		**	**	**	**			*		***	Turbines and Generators
**													*	ENVIRONMENTAL QUALITY
***													*	Mining and Raw Materials Extraction
**														Pollution
***														Recycling and Solid Waste Disposal
			*		*		**	*			*		***	Reliability, Safety, Maintainability
	**			*			*				*		***	HEALTH SERVICES
	***			*			*				*		***	Artificial Organs
	*			*	*	*	*	*			*		***	Prosthetic Devices
				*			**						**	HOUSING AND OTHER CONSTRUCTION
	*			*			**						*	Individual and Multiple Unit Dwellings
							*							Plumbing, Heating, Electrical, etc.
			*		*	*	*	*					**	PRODUCTION EQUIPMENT
			*		*	*	*	*			*		**	Machine Tools
*		*	**		**	*	*	*					*	Process Equipment
			**	*	**	*	**	*			*		*	TRANSPORTATION EQUIPMENT
		*	***		**	*	***	*			*		***	Aircraft
			**		**	**	***	**			**		**	Automotive
			*		*		*						*	Guided Ground Transportation

TABLE 5.9d Priorities for Applied Research -- Disciplines

	Earth Sciences	Analytical Chemistry	Physical Chemistry	Organic and Polymer Chemistry	Inorganic Chemistry	Solid State Chemistry	Solid State Physics	Ceramics and Glass	Polymer Processing	Extractive Metallurgy	Metals and Inorganic Materials Processing	Physical Metallurgy	Chemical Engineering	Mechanical Engineering	Electronic Engineering	Aerospace Engineering	Nuclear Engineering	Bioengineering	Civil and Environmental Engineering
COMMUNICATIONS, COMPUTERS AND CONTROL		*	*		*	***	***	**			*	*			***				
Computers		*	*		*	***	***	**				*			***				
Electronic Components		*	**		*	***	***	**			*	*			***				
Telephone and Data Networks and Equipment		*	*		*	***	***	***			*				***				
CONSUMER GOODS		*	*	**	*	*	*	*	**				*	*					
Apparel and Textiles		*	**	***					***				*	*					
Household Appliances - Electronic		*	*	*	*	***	***	**	*		*				***				
Packaging and Containers		*	*	**				**	**				*	*					
Printing and Photography		*	**	**	**		**		*										
DEFENSE AND SPACE			*			*	*	*			**	**		*	*	*			
Military Aircraft								*			***	***		**		**			
Missiles			*			*	*	*			**	**		*	*	**			
Naval Vessels											*	**		*					
Ordnance and Weapons			*	*		*	*	*			*	***		**	*	*			
Radar and Military Communications			*		*	***	***	**			*				***				
Spacecraft			*	*	*	*	*	*			*	**		*	*	**			
Undersea Equipment							*	*			*	**		*					
ENERGY			*		*	**	**	*			*	**		*					
Batteries and Fuel Cells		*	***		**	***	**	*					*						
Direct Conversion			*		*	***	***	*			*				*				
Electric Transmission and Distributors			*			**	***	*			*	**			*				
Nuclear Reactors			*			*	**	*			**	***	*	*			***		
Thermonuclear Fusion			*		*	**	***	*			*	***	*	*			***		
Turbines and Generators			*				*	*			***	***		**					
ENVIRONMENTAL QUALITY	*	*	*	*	*			*		*	*	*	**	*					*
Mining and Raw Materials Extraction	**	*	*		**					***	**	*	**	*					*
Pollution		**	**	*	**	*		*			*		**						**
Recycling and Solid Waste Disposal	*	*	*	*	*			*		*	*		**	*					**
Reliability, Safety, Maintainability				*		*	*	*	*		**	**	*	**	*			*	*
HEALTH SERVICES		*	*	**		*		*	*					*				***	
Artificial Organs		*	**	***		*		*	**					*				***	
Prosthetic Devices		*	*	**	*	*		**	*		*	*		*				***	
HOUSING AND OTHER CONSTRUCTION				*				*	*					*					*
Individual and Multiple Unit Dwellings				*				*	*				*	*					*
Plumbing, Heating, Electrical, etc.								*			*			*					
PRODUCTION EQUIPMENT								*			**	**		**					
Machine Tools								*			**	**		**					
Process Equipment			*					*			***	*	*	**					
TRANSPORTATION EQUIPMENT								*	*		**	**		**	*				
Aircraft				*					*		**	***		***	*	***			
Automotive			*	*			*	*	*		**	**	*	**					
Guided Ground Transportation							*				*	**		*	*				*

TABLE 10a Rank Ordering of Priority for Applied Research -- Properties of Materials (Corrected for Familiarity)

Atomic Structure	Microstructure (Electron Microscope Level)	Microstructure (Optical Microscope Level)	Thermodynamic	Thermal	Mechanical and Acoustic	Optical	Electrical	Magnetic	Dielectric	Nuclear	Chemical	Biological	
5	3	8	9	10	13	4	1	7	2	11	6	12	COMMUNICATIONS, COMPUTERS AND CONTROL
3	1	7	8	12	11	9	2	4	5	10	6	13	Computers
4	1	11	10	9	13	7	2	8	3	6	5	12	Electronic Components
6	4	8	10	11	5	2	9	12	3	13	1	7	Telephone and Data Networks and Equipment
9	4	5	10	6	3	7	8	13	11	12	2	1	CONSUMER GOODS
4	3	7	8	6	5	12	11	13	10	9	2	1	Apparel and Textiles
5	2	8	11	7	9	3	4	12	6	13	10	1	Household Appliances - Electronic
9	4	7	6	5	2	10	12	13	11	8	3	1	Packaging and Containers
1	4	3	9	13	10	1	7	12	8	6	5	2	Printing and Photography
9	3	8	7	5	1	10	12	13	11	4	2	6	DEFENSE AND SPACE
3	1	7	6	5	4	8	13	12	11	10	2	9	Military Aircraft
5	4	11	2	2	9	6	10	13	8	1	7	12	Missiles
9	3	8	7	13	1	12	10	11	5	4	2	6	Naval Vessels
9	4	6	11	7	2	5	12	13	10	3	1	8	Ordnance and Weapons
5	3	10	12	13	7	6	2	11	4	1	8	9	Radar and Military Communications
0	5	12	7	2	1	6	8	13	11	3	4	9	Spacecraft
0	2	7	13	11	3	8	12	5	6	9	1	4	Undersea Equipment
8	2	10	6	5	4	13	7	12	11	3	1	9	ENERGY
9	5	10	3	7	11	13	2	12	6	8	1	4	Batteries and Fuel Cells
7	5	12	6	1	11	4	3	13	10	8	2	9	Direct Conversion
8	1	11	7	5	4	13	2	9	6	12	3	10	Electric Transmission and Distribution
6	4	8	9	7	3	12	11	13	10	2	1	5	Nuclear Reactors
5	4	8	10	6	1	13	12	11	9	3	2	7	Thermonuclear Fusion
7	2	6	5	4	3	13	9	12	8	11	1	10	Turbines and Generators
3	5	8	4	9	7	11	12	6	10	3	2	1	ENVIRONMENTAL QUALITY
3	8	6	3	9	10	11	12	4	5	7	1	2	Mining and Raw Materials Extraction
2	4	11	5	7	13	6	9	10	8	3	2	1	Pollution
3	10	12	3	7	6	8	11	5	9	4	2	1	Recycling and Solid Waste Disposal
3	6	11	12	8	3	7	5	4	9	10	2	1	Reliability, Safety, Maintainability
0	3	5	8	11	4	13	6	12	9	7	2	1	HEALTH SERVICES
7	3	6	10	12	5	13	4	11	9	8	2	1	Artificial Organs
11	4	5	8	10	3	13	7	12	9	6	2	1	Prosthetic Devices (including dental)
13	5	6	10	4	3	8	11	12	9	7	2	1	HOUSING AND OTHER CONSTRUCTION
13	7	6	12	4	3	5	10	11	8	9	2	1	Individual and Multiple Unit Dwellings
13	11	8	7	4	3	6	5	12	9	10	2	1	Plumbing, Heating, Electrical, etc.
13	3	7	10	5	1	8	6	11	9	12	2	4	PRODUCTION EQUIPMENT
7	1	2	6	4	3	9	13	12	10	11	5	8	Machine Tools
13	5	12	8	4	1	10	6	3	9	11	2	7	Process Equipment
8	3	5	7	6	2	13	10	13	11	9	1	4	TRANSPORTATION EQUIPMENT
7	1	6	5	2	4	9	11	13	10	12	3	8	Aircraft
9	4	6	5	7	3	13	12	10	11	8	1	2	Automotive
12	7	6	8	9	1	11	4	5	10	13	2	3	Guided Ground Transportation

TABLE 5.10b Rank Ordering of Priority for Applied Research -- Classes of Materials (Corrected for Familiarity)

Ceramics	Glasses and Amorphous Materials	Elemental and Compound Semiconductors	Inorganic, Non-Metallic Elements and Compounds	Ferrous Metals and Alloys	Non-Ferrous Structural Metals and Alloys	Non-Ferrous Conducting Metals and Alloys	Plastics	Fibers and Textiles	Rubbers	Composites	Organic and Organo-Metallic Compounds	Thin Films	Adhesives, Finishes, Coatings, Seals	Lubricants, Oils, Solvents, Cleansers	Prosthetic and Medical Materials	Plain and Reinforced Concrete	Asphaltic and Bituminous Materials	Wood and Paper	
7	4	2	8	18	19	10	5	13	12	11	3	1	6	9	16	17	15	14	COMMUNICATIONS, COMPUTERS AND CONTROL
7	4	3	8	11	19	10	5	18	15	12	2	1	6	9	17	16	14	13	Computers
5	2	3	8	18	19	10	7	13	12	11	4	1	6	9	15	17	14	16	Electronic Components
10	3	6	7	17	15	11	1	8	13	9	5	2	4	12	19	18	16	14	Telephone and Data Networks and Equipment
15	10	14	12	13	11	17	2	6	7	5	3	8	1	9	18	19	16	4	CONSUMER GOODS
16	12	13	10	17	19	15	3	2	4	6	5	9	1	8	11	18	14	7	Apparel and Textiles
8	4	6	11	18	14	13	1	9	10	3	7	2	5	12	19	15	16	17	Household Appliances - Electronic
14	9	18	12	10	7	17	2	11	8	5	4	6	3	13	16	19	15	1	Packaging and Containers
19	10	12	15	11	14	16	3	8	9	7	2	6	1	5	18	17	13	4	Printing and Photography
9	10	14	12	13	6	18	3	7	5	2	8	11	1	4	17	19	15	16	DEFENSE AND SPACE
7	10	13	8	14	6	19	5	11	4	3	9	12	1	2	17	18	15	16	Military Aircraft
4	8	3	2	18	14	19	5	11	7	1	12	9	6	10	15	16	13	17	Missiles
18	15	12	13	14	9	19	4	7	3	2	6	11	1	5	17	10	8	16	Naval Vessels
11	10	13	12	6	7	19	1	8	4	3	9	18	2	5	15	16	14	17	Ordnance and Weapons
5	3	4	7	18	19	15	1	11	12	10	6	2	8	9	17	14	13	16	Radar and Military Communications
6	8	10	13	15	11	14	4	5	9	3	7	12	2	1	19	18	16	17	Spacecraft
9	5	16	19	8	4	12	7	11	2	3	10	15	1	6	18	14	13	17	Undersea Equipment
1	14	18	8	16	6	4	11	15	9	3	5	13	2	7	19	12	10	17	ENERGY
3	8	13	1	19	18	10	4	9	6	7	2	12	5	17	15	16	11	14	Batteries and Fuel Cells
1	8	4	7	19	18	9	10	11	14	5	6	2	3	13	16	15	12	17	Direct Conversion
9	14	19	18	16	12	1	4	8	7	3	6	13	2	10	17	15	11	5	Electric Transmission and Distributors
2	14	18	13	4	1	16	12	15	10	7	9	19	5	6	17	3	8	11	Nuclear Reactors
2	8	19	14	10	1	4	16	13	9	3	11	18	6	7	17	5	12	15	Thermonuclear Fusion
5	15	19	10	7	4	13	12	9	8	3	6	14	1	2	18	17	11	16	Turbines and Generators
13	15	19	11	16	9	14	3	7	4	10	2	17	8	6	18	12	5	1	ENVIRONMENTAL QUALITY
6	14	17	10	9	2	15	12	16	7	13	5	18	4	3	19	8	1	11	Mining and Raw Materials Extraction
11	15	19	9	18	14	16	4	7	8	10	1	12	5	3	17	13	6	2	Pollution
16	12	17	14	9	6	10	2	4	3	11	8	18	15	7	19	13	5	1	Recycling and Solid Waste Disposal
15	11	7	18	17	14	19	6	5	3	4	8	9	1	12	2	13	10	16	Reliability, Safety, Maintainability
9	10	19	13	16	8	17	2	6	4	5	7	12	3	11	1	18	15	14	HEALTH SERVICES
11	12	15	13	16	9	14	2	5	3	6	7	8	4	10	1	17	18	19	Artificial Organs
9	10	19	12	16	7	18	2	5	6	4	8	13	3	11	1	17	15	14	Prosthetic Devices
11	12	19	15	13	10	17	2	6	8	7	9	16	1	14	18	4	3	5	HOUSING AND OTHER CONSTRUCTION
9	12	18	15	14	10	16	4	6	7	8	11	17	1	13	19	3	5	2	Individual and Multiple Unit Dwellings
12	13	17	16	2	3	9	1	11	6	5	7	19	4	10	18	14	8	15	Plumbing, Heating, Electrical, Etc.
12	18	16	15	7	4	14	6	9	2	8	5	11	3	1	17	19	13	10	PRODUCTION EQUIPMENT
8	19	18	16	2	4	17	11	12	3	6	5	15	7	1	9	14	10	13	Machine Tools
15	18	17	14	7	3	13	6	9	2	8	4	12	5	1	19	16	10	11	Process Equipment
10	11	17	12	9	7	14	4	6	3	5	8	16	2	1	19	18	13	15	TRANSPORTATION EQUIPMENT
10	11	12	8	14	7	18	5	9	3	4	6	13	1	2	17	19	16	15	Aircraft
10	12	16	11	7	8	13	4	5	3	6	9	19	2	1	17	18	14	15	Automotive
12	13	19	18	10	6	9	5	11	4	3	14	17	2	1	16	7	8	15	Guided Ground Transportation

TABLE 5.10c Rank Ordering of Priority for Applied Research -- Processes (Corrected for Familiarity)

Extraction, Purification, Refining	Synthesis and Polymerization	Solidification and Crystal Growth	Metal Deformation and Processing	Plastics Extrusion and Molding	Heat Treatment	Material Removal	Joining	Powder Processing	Vapor and Electrodeposition, Epitaxy	Radiation Treatment	Plating and Coating	Chemical	Testing and Non-Destructive Testing	
5	8	6	14	11	13	10	9	12	1	3	4	2	7	COMMUNICATIONS, COMPUTERS AND CONTROL
9	6	11	14	10	13	5	7	12	1	4	2	3	8	Computers
6	7	5	14	11	13	10	9	12	2	3	4	1	8	Electronic Components
1	4	10	13	6	11	12	8	14	5	9	3	2	7	Telephone and Data Networks and Equipment
13	2	14	12	1	9	6	4	11	10	8	3	5	7	CONSUMER GOODS
13	1	9	14	3	8	12	2	11	10	5	7	4	6	Apparel and Textiles
3	7	9	8	1	14	12	6	11	2	13	4	5	10	Household Appliances - Electronic
13	5	14	9	1	6	11	3	12	8	7	2	10	4	Packaging and Containers
9	1	13	14	4	8	7	11	10	5	6	3	2	12	Printing and Photography
12	4	14	5	6	13	7	1	8	11	10	3	9	2	DEFENSE AND SPACE
14	7	11	5	10	8	4	1	6	12	13	3	9	2	Military Aircraft
8	1	12	13	10	14	11	7	9	3	6	2	5	4	Missiles
11	3	12	9	4	14	7	1	6	10	13	2	5	8	Naval Vessels
13	2	14	1	3	7	8	6	9	12	11	4	10	5	Ordnance and Weapons
9	5	10	13	8	14	12	6	11	3	1	7	4	2	Radar and Military Communications
11	4	13	9	6	14	7	1	12	8	5	2	10	3	Spacecraft
12	7	14	4	3	5	8	1	9	13	11	2	10	6	Undersea Equipment
7	6	14	5	13	9	12	1	4	10	8	2	11	3	ENERGY
7	5	10	12	4	14	13	9	1	6	11	3	2	8	Batteries and Fuel Cells
8	3	11	14	10	13	12	5	9	2	1	4	7	6	Direct Conversion
4	1	14	2	5	6	12	7	8	10	13	3	11	9	Electric Transmission and Distributors
8	11	14	3	10	7	9	1	4	13	6	5	12	2	Nuclear Reactors
7	13	14	4	12	6	9	2	5	8	10	3	11	1	Thermonuclear Fusion
13	6	9	4	11	8	3	2	7	10	12	1	14	5	Turbines and Generators
1	2	14	11	3	13	8	10	6	12	5	7	4	9	ENVIRONMENTAL QUALITY
1	3	9	14	2	13	4	11	6	12	8	10	7	5	Mining and Raw Materials Extraction
1	2	14	12	6	13	8	10	7	11	4	5	3	9	Pollution
1	3	14	5	2	9	4	8	7	13	6	12	10	11	Recycling and Solid Waste Disposal
5	3	14	11	8	9	12	2	10	13	4	7	6	1	Reliability, Safety, Maintainability
9	1	14	12	2	13	8	4	10	11	7	5	6	3	HEALTH SERVICES
10	1	14	12	4	13	9	2	11	8	7	5	6	3	Artificial Organs
7	1	14	12	2	13	6	4	9	11	10	3	8	5	Prosthetic Devices
13	3	14	6	2	12	9	1	10	11	8	4	7	5	HOUSING AND OTHER CONSTRUCTION
12	4	14	5	1	11	10	2	9	13	8	3	7	6	Individual and Multiple Unit Dwellings
10	2	9	5	1	8	11	3	13	7	12	4	6	14	Plumbing, Heating, Electrical, Etc.
14	5	13	2	3	10	6	1	8	12	9	7	11	4	PRODUCTION EQUIPMENT
13	7	14	6	10	5	1	2	8	12	11	3	9	4	Machine Tools
10	3	12	2	4	9	6	1	5	14	11	7	13	8	Process Equipment
12	8	14	6	2	9	4	1	5	11	13	3	10	7	TRANSPORTATION EQUIPMENT
14	4	9	10	5	11	3	1	7	12	13	2	8	6	Aircraft
13	9	14	6	1	7	3	2	4	12	11	5	10	8	Automotive
9	5	14	1	2	8	10	3	6	12	13	4	11	7	Guided Ground Transportation

TABLE 5.10d Rank Ordering of Priority for Applied Research -- Disciplines (Corrected for Familiarity)

Earth Sciences	Analytical Chemistry	Physical Chemistry	Organic and Polymer Chemistry	Inorganic Chemistry	Solid State Chemistry	Solid State Physics	Ceramics and Glass	Polymer Processing	Extractive Metallurgy	Metals and Inorganic Materials Processing	Physical Metallurgy	Chemical Engineering	Mechanical Engineering	Electronic Engineering	Aerospace Engineering	Nuclear Engineering	Bioengineering	Civil and Environmental Engineering	
19	3	10	8	9	2	6	4	5	13	7	14	11	12	1	15	17	16	18	COMMUNICATIONS, COMPUTERS AND CONTROL
19	6	11	7	8	2	9	5	3	10	4	11	14	12	1	15	17	16	18	Computers
19	3	7	8	10	2	5	4	6	14	9	13	11	16	1	12	15	17	18	Electronic Components
19	5	12	9	8	6	13	3	4	10	2	16	11	7	1	18	17	14	15	Telephone and Data Networks Equipment
19	9	13	2	11	10	17	12	1	14	8	15	4	3	6	18	16	7	5	CONSUMER GOODS
18	8	4	2	10	11	13	12	1	15	16	19	3	6	9	17	14	7	5	Apparel and Textiles
19	11	8	4	12	7	10	2	1	15	5	13	9	6	3	18	14	16	17	Household Appliances - Electronic
15	14	17	6	19	12	11	8	3	13	7	10	4	2	9	16	18	5	1	Packaging and Containers
19	5	8	1	4	6	17	14	2	9	10	16	3	7	12	15	18	13	11	Printing and Photography
19	13	16	5	15	14	17	11	4	18	6	8	10	3	2	1	7	9	12	DEFENSE AND SPACE
19	10	15	6	14	8	9	12	3	18	5	7	16	4	2	1	17	11	13	Military Aircraft
11	15	9	5	10	6	8	12	3	19	17	18	14	7	1	2	4	16	13	Missiles
17	18	14	4	9	15	16	11	3	19	12	8	13	6	1	10	2	5	7	Naval Vessels
19	10	11	2	12	13	14	15	3	18	4	5	8	1	7	9	6	16	17	Ordnance and Weapons
19	11	13	8	10	1	14	7	5	9	6	18	15	4	2	3	12	16	17	Radar and Military Communications
15	12	17	3	14	11	16	8	4	19	18	13	9	6	2	1	7	5	10	Spacecraft
11	19	18	5	16	17	15	3	1	12	10	7	14	2	4	13	6	9	8	Undersea Equipment
19	10	11	15	14	5	9	12	13	17	3	8	4	2	6	18	1	16	7	ENERGY
19	6	3	5	2	4	9	10	7	18	13	17	1	15	8	16	14	11	12	Batteries and Fuel Cells
19	13	15	8	12	4	5	7	10	18	9	17	16	3	1	11	2	14	6	Direct Conversion
19	11	15	5	12	4	13	14	2	7	1	3	10	8	6	17	18	16	9	Electric Transmission and Distributors
18	7	14	15	11	8	13	12	17	10	5	6	3	2	16	19	1	9	4	Nuclear Reactors
19	7	16	14	15	9	12	11	13	10	2	5	3	4	8	18	1	17	6	Thermonuclear Fusion
19	14	16	9	10	13	15	5	4	18	2	3	7	1	6	12	11	17	8	Turbines and Generators
6	8	14	7	11	18	19	15	9	4	10	17	2	5	13	16	12	3	1	ENVIRONMENTAL QUALITY
2	9	14	10	8	16	17	19	13	1	6	15	4	5	7	18	11	12	3	Mining and Raw Materials Extraction
8	5	7	3	9	17	18	15	6	12	13	19	4	10	14	16	11	2	1	Pollution
9	8	15	7	12	18	19	11	3	4	10	16	5	6	17	14	13	2	1	Recycling and Solid Waste Disposal
19	14	18	7	16	10	11	15	8	17	9	13	5	2	3	12	6	1	4	Reliability, Safety, Maintainability
18	5	10	2	9	14	19	8	3	16	11	15	7	4	6	17	13	1	12	HEALTH SERVICES
19	5	9	2	11	8	18	13	3	17	10	16	7	4	6	15	12	1	14	Artificial Organs
18	5	11	2	9	14	19	6	3	15	7	12	10	4	8	16	17	1	13	Prosthetic Devices
13	19	17	3	10	12	18	6	2	15	9	11	8	4	7	16	14	5	1	HOUSING AND OTHER CONSTRUCTION
8	18	19	4	12	11	17	7	3	15	9	16	10	2	5	14	13	6	1	Individual and Multiple Unit Dwellings
18	12	14	3	16	6	13	9	2	15	5	8	7	1	10	19	17	11	4	Plumbing, Heating, Electrical, Etc.
19	16	17	8	15	14	18	12	3	10	2	6	5	1	4	13	11	9	7	PRODUCTION EQUIPMENT
18	17	14	16	8	10	19	7	3	11	1	4	9	2	15	6	12	5	13	Machine Tools
19	17	9	6	15	11	16	14	4	5	2	8	3	1	7	18	13	12	10	Process Equipment
19	15	17	4	13	12	18	10	2	14	6	8	9	1	3	7	16	11	5	TRANSPORTATION EQUIPMENT
19	13	14	3	10	11	15	6	2	18	9	7	8	5	1	4	17	12	16	Aircraft
19	11	16	4	15	13	18	9	2	14	3	8	7	1	6	12	17	10	5	Automotive
12	17	18	8	13	14	19	16	5	10	4	6	9	2	1	7	15	11	3	Guided Ground Transportation

PRIORITIES FOR APPLIED RESEARCH BY AREA OF IMPACT

In the remainder of this chapter data on priorities in Applied Research and Engineering are presented individually for each of the nine areas of impact. The figures such as Fig. 5.2 are graphical representations of the priority for applied research in the particular Area of Impact plotted against the familiarity of the respondees with that area of impact. Both ratings are on a 0–100 scale, although only the 10–80 portion of the horizontal scale is presented. The familiarity rating is that of only the respondees who chose the particular area of impact. The overall priority rating for the areas and sub-areas of impact are presented in tabular form as in Table 5.11. In addition, the comments from page 2 of the questionnaire have been summarized and are presented below for each area of impact. The number of comments made in each sub-area is indicated in parentheses at the top of the comments pages.

Area 10 Communications, Computers and Control

The Priority for Applied Research in Communications, Computer and Control is shown plotted against the familiarity of the respondees with each of the categories in Fig. 5.2. The categories which have high absolute priority, that is, those at the top of the figure as well as those on the upper envelope should be accorded highest priority. Electrical Properties not surprisingly received the highest rating with the Semiconductors and Thin Films being the Materials given highest priority. Plastics, Organic Compounds and Adhesives are on the upper envelope for their importance as encapsulants, although the prople who chose these areas are not very familiar with these materials. The Processes of Vapor Deposition, Chemical Processing, Radiation Treatment (ion implantation), and Plating receive high priority and the Disciplines Solid State Physics, Solid State Chemistry and Electrical Engineering are most relevant.

The comments have been grouped according to the area or sub-area in which they were made rather than under the groupings indicated by Fig. 5.2. Some of the respondees chose to comment generally on the area of Communications, Computers and Control and high priority was accorded to various forms of memory and to displays with various aspects of semiconductor technology being recommended for further research. Optical Communications were also mentioned by several people. The sub-area Commercial Radio and TV Equipment had no strong indication of areas for applied research. The sub-area of Computers emphasized many of the same areas which were emphasized on the overall comments for this area. The sub-area of Electronic Components, which is an area where extensive applied materials research is concentrated, came in for the greatest number of comments. There were detailed comments on many of the categories which are indicated to be important in Fig. 5.2. Defects and reliability are important topics, and chemical processing, surfaces, and optical properties are important areas for research. Optical communications and memory also rated high. Materials under Electronic Components included the characterization synthesis of raw materials, of thin films and of optical materials. The Processes of chemical doping, crystal growth, encapsulation and general improvement in semiconductor processing were given high priority. In the sub-area of Equipment for Guidance and Control of Transportation several people indicated needs for improved guidance systems. Under the subarea of Teaching Equipment, teaching aids and associated displays were ranked as areas requiring further research. Under the area Telephone and Data Network Equipment optical transmission and integrated optics as the communications media of the future received the highest priority rating for further research.

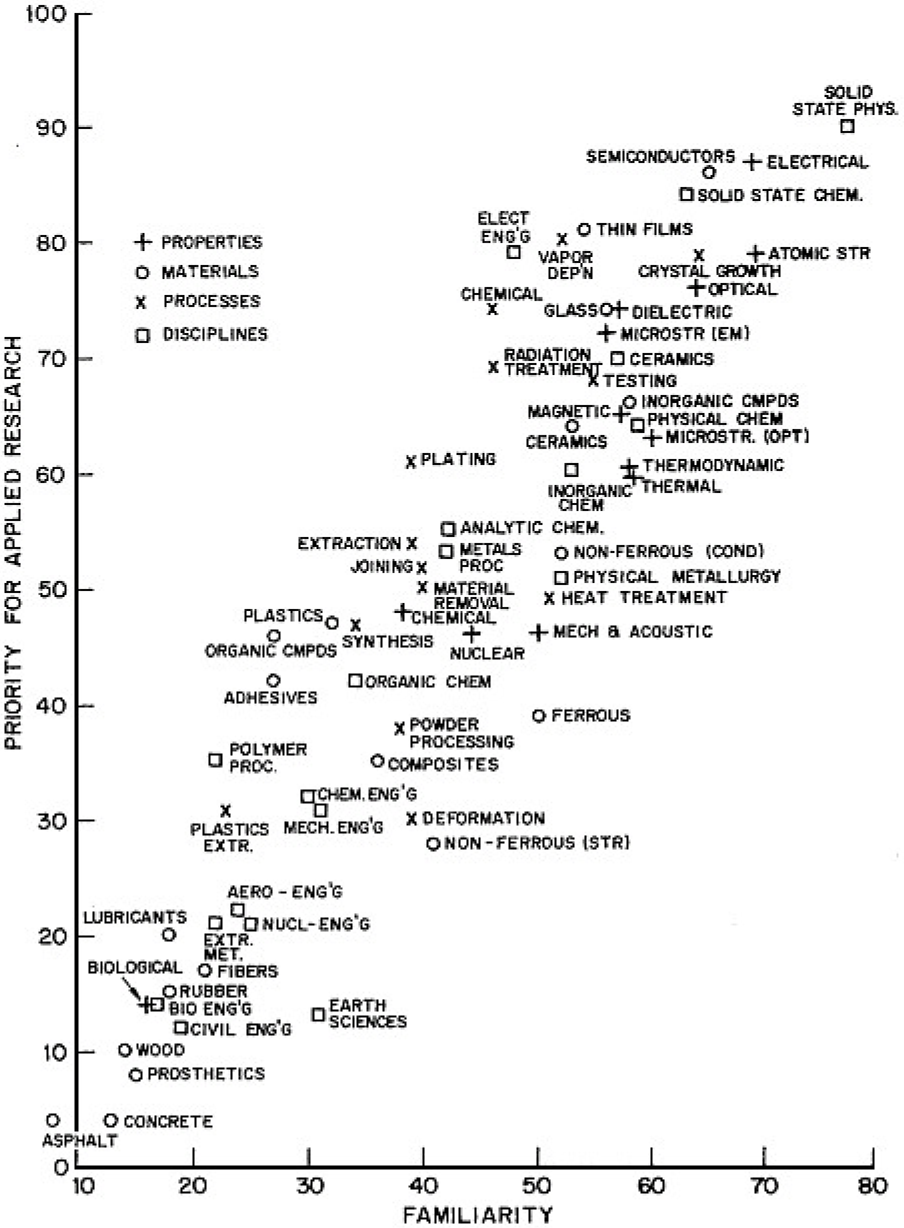

FIGURE 5.2 PRIORITY FOR APPLIED RESEARCH—AREA 10 COMMUNICATIONS, COMPUTERS AND CONTROL

TABLE 5.11 Priority for Applied Research - Area 10 - Communications, Computers and Control

COMMUNICATIONS, COMPUTERS AND CONTROL	Computers	Electronic Components	Telephone and Data Networks Equipment	
79	79	82	75	Atomic Structure
72	72	76	73	Microstructure (Electron Microscope Level)
63	61	62	69	Microstructure (Optical Microscope Level)
60	60	62	60	Thermodynamic
60	57	63	56	Thermal
46	44	43	61	Mechanical and Acoustic
76	73	74	86	Optical
87	87	90	77	Electrical
65	74	63	56	Magnetic
74	72	74	79	Dielectric
46	42	53	37	Nuclear
48	42	51	53	Chemical
14	12	12	18	Biological
64	57	69	59	Ceramics
74	70	76	43	Glasses and Amorphous Materials
86	84	91	75	Elemental and Compound Semiconductors
66	64	66	72	Inorganic, Nonmetallic Elements and Compounds
39	46	35	38	Ferrous Metals and Alloys
28	26	25	32	Nonferrous Structural Metals and Alloys
53	52	54	54	Nonferrous Conducting Metals and Alloys
47	44	43	57	Plastics
17	12	14	29	Fibers and Textiles
15	12	12	22	Rubbers
35	28	34	40	Composites
46	51	45	47	Organic and Organo-Metallic Compounds
81	86	83	78	Thin Films
42	37	42	46	Adhesives, Coatings, Finishes, Seals
20	20	19	19	Lubricants, Oils, Solvents, Cleansers
8	4	11	2	Prosthetic and Medical Materials
4	3	3	4	Plain and Reinforced Concrete
4	3	3	4	Asphaltic and Bituminous Materials
10	8	6	15	Wood and Paper

COMMUNICATIONS, COMPUTERS AND CONTROL	Computers	Electronic Components	Telephone and Data Networks Equipment	
54	49	61	53	Extraction, Purification, Refining
47	48	49	63	Synthesis and Polymerization
79	76	86	66	Solidification and Crystal Growth
30	27	27	32	Metal Deformation and Processing
31	29	26	42	Plastics Extrusion and Molding
49	44	50	51	Heat Treatment
50	48	53	47	Material Removal
52	47	54	53	Joining
38	34	40	30	Powder Processing
80	80	88	71	Vapor and Electrodeposition, Epitaxy
69	67	78	59	Radiation Treatment
61	63	63	60	Plating and Coating
74	71	80	67	Chemical
68	63	70	69	Testing and Nondestructive Testing
13	5	12	10	Earth Sciences
55	52	59	57	Analytical Chemistry
64	63	67	62	Physical Chemistry
42	43	42	45	Organic and Polymer Chemistry
60	59	62	63	Inorganic Chemistry
84	84	66	77	Solid State Chemistry
90	91	93	82	Solid State Physics
70	67	71	80	Ceramics and Glass
35	35	33	46	Polymer Processing
21	19	21	22	Extractive Metallurgy
53	46	54	63	Metals and Inorganic Materials Processing
51	51	53	45	Physical Metallurgy
32	27	33	31	Chemical Engineering
31	29	28	39	Mechanical Engineering
79	81	79	77	Electronic Engineering
22	21	23	12	Aerospace Engineering
21	14	24	10	Nuclear Engineering
14	11	13	9	Bioengineering
12	5	10	17	Civil and Environmental Engineering

10 Communications, Computers and Control (49)

***Memory: magnetic bubble systems; bubble domain devices; bubble memory film substrates; bubble materials and devices; low cost memories; faster response; increase memory capacity; magnetic recording heads; optical memories; new storage media; better library storage (microfilm)

***Displays: light emitting diodes; solid state displays; alternatives to CRT; displays for interactive systems; improved display of processes information

***Semiconductors: reliability; improved LSI circuits for logic and memory; ion implantation; yield; control boundaries between semiconductors and insulators; perfection of thin films, epitaxy; oxide, adhesion; diffusion purity; processing of compound semiconductors; thermal conductivity of substrates

**Optical processing of signals; integrated optics; development of dielectric materials for optical devices

*Electronic properties of organic materials

*Demonstration devices for teaching

*Dissemination of information

*Reliable switches; electrical connections

*Aids for blind and deaf

*Direct coupling between computer and brain; coupling to nerves

11 Commercial Radio and TV Equipment (5)

*Miniaturization
*RF power generators
*Low power detectors
*Optical components

12 Computers (85)

***Memories: increased speed; reduced size; reduced cost; use of new materials such as bubbles, optical storage, amorphous materials
***Displays: large area displays; fast displays; LED's; better phosphors
***Integrated Circuits: improved materials, further miniaturization, larger LSI's
**High temperatures: response of components to high temperature; higher operating temperature components
*Conducting plastics
*Improved interconnection methods
*Encapsulation
*Fiber optics for transmission

13 Electronic Components (244)

Properties

***Defects: control of defects; study structural defects; develop defect free materials

***Chemical: corrosion; connectors; contacts; interconnects; compatibility in environment

***Surfaces: surface states; surface effects in semiconductors and insulators; interface compatibility; interface imperfections

***Reliability: electromigration; effects of random voltage spikes; longer life needed

***Optical properties: displays; LED's; variable handgap semiconductors; blue luminescent diodes and lasers; better imaging materials; electroluminescence for all colors; wider spectral spread; efficient LED's

***Optical communications: components; solid state lasers; diodes; LED's; NLO's; sensors; logic elements; amplifiers; detectors; electro-optic microelectronics; laser windows; optical damage

***Memory; solid state memory; high density storage; magnetic storage; bubbles; IR storage

**Dielectric: better high voltage and high temperature dielectrics; high dielectric strength film insulators; more reliable capacitors

**Superconductivity: T_c>liq H_2; development of components; Josephson devices; brushes and contacts for superconducting motors

**Radiation: hardened devices for nuclear environments

**IR detectors: imaging systems; upconverters

**Charge coupled devices

**Microwave generators: more efficiency; higher power; higher frequency

*Thermoelectric cooler for liquid nitrogen temperature

*High temperature semiconductors

*Electron emissions: improve emission for better CRT's and displays

Materials

***Raw materials: purity; characterization; synthesis
***Thin films: of II–VI's; for memories; control of metallization
***Optical materials: lasers; diodes; LED's; NLO's
**Ceramics for substrates
**Magnetic materials: for bubble memories; permanent magnetic materials
**Magnetic bubble materials
*Amorphous semiconductors: switching
*Semiconducting plastics; organic materials

Processes

***Chemical doping: control of doping; distribution of dopants; uniformity of dopants; more precision in control
***Crystal growth: larger, more perfect crystals; monolithic processing for III–V's
***Joining: seals; encapsulants; conducting adhesives; glass/metal seals; coatings; glass for passivation
***Processing: yields; improve uniformity; reduce cost; improve processing; better diodes; more miniaturization; control of LSI
**Radiation treatment: ion implantation; radiation damage
**Testing: non-destructive characterization

14 Equipment for Guidance and Control of Transportation (7)

***Guidance: linear and angular position transducers for inertial navigation; solid state high frequency source for radar; lightweight guidance systems; waveguides for guidance

***Displays: Better phosphors; photovoltaic arrays; opto-electronic components

15 Teaching Equipment (25)

***Teaching aids: computer assisted programs for medical and dental students; cheap reliable interactive computers; sight, sound, action equipment; audio visual aids for medical and dental students

***Displays: simple projectors; dustless substitute for chalk; gas display panels; improved life phosphors; liquid crystal displays; cheaper hard copy computer terminals

**Better duplication processes; cheaper textbooks; substitute for textbooks

**Optical demonstration units; lower cost laboratory materials; less expensive, high quality single crystals for undergraduate solid state laboratories; heat and thermodynamics demonstration unit

16 Telephone and Data Network Equipment (55)

***Optical transmission: method of making high purity glass fibers; low loss optical fibers; high purity glasses and how to fabricate them into waveguides; laser light transmission line; optical waveguides; low loss materials; high transmission glasses; low attenuation fibers

***Integrated Optics; optical signal processing; large non-linear optical coefficients; reliable optical sources; high acousto-optic figure of merit; materials which can perform electronic functions; optical modulators; integrated optical processing; light modulation

*Lower cost LSI's; better reliability and reproducibility of semiconductor devices; new or improved materials for LSI

*Displays: improved display materials; lower cost displays

*Home Uses: coaxial cable system linking the home; memory for home use; inhouse printing system

*Rapid access storage for public libraries; remote data terminals; information storage; memory device development; high density storage

*Conserve critical materials

*Amorphous semiconductor switches; new switching materials

*Wires, cables; stability of backplane wiring

*Degradation of organic materials; improved polymeric materials; molding equipment; finishes

Area 20 Consumer Goods

Under Consumer Goods the Properties that received the highest rating, as shown in Fig. 5.3, are Mechanical Properties, Chemical Properties and Biological Properties. This latter refers to biodegradability of consumer goods. Plastics and Adhesives for the Materials rated highest. The Processes of Synthesis and Plastics Extrusion were rated highly and the important Disciplines were Polymer Processing, Organic Chemistry, Chemical Engineering and Mechanical Engineering.

The comments on Consumer Goods as a general area emphasized the importance of research to improve durability and reliability. There were no comments under Apparel and Textiles although fibers appeared fairly high in Fig. 3. In the sub-area of Furniture flammability and mechanical properties received the highest priority. For Electronic Household Appliances, display media received high priority. For the sub-area of Nonelectronic Household Appliances, reliability was important along with mechanical properties and fabrication methods. There were no comments on Leisure and Sports Equipment. Under the sub-area of Packaging and Containers, mechanical properties and recyclability of packaging materials received high priority and the importance of further research on glass containers was emphasized. In the area of Printing and Photography further research and improvements in both the product and understanding of photographic emulsions were given high priority.

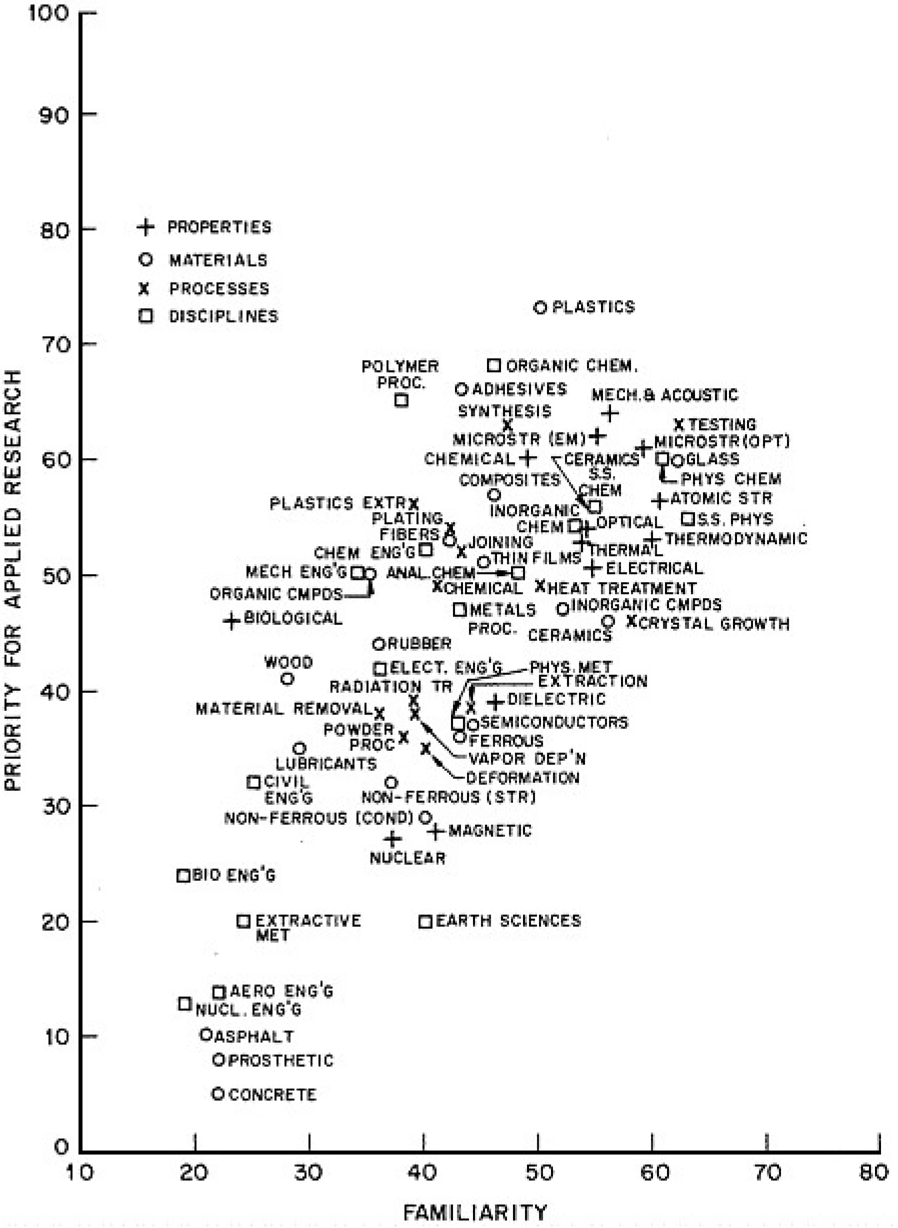

FIGURE 5.3 PRIORITY FOR APPLIED RESEARCH—AREA 20 CONSUMER GOODS

TABLE 5.12 Priority for Applied Research _ Area 20 _ Consumer Goods

CONSUMER GOODS	Apparel and Textiles	Household Appliances - Electonics	Packaging and Containers	Printing and Photography	
55	64	71	57	63	Atomic Structure
62	70	64	70	71	Microstructure (Electron Microscope Level)
61	64	57	59	69	Microstructure (Optical Microscope Level)
53	59	56	68	49	Thermodynamic
53	59	60	52	44	Thermal
64	71	51	85	38	Mechanical and Acoustic
54	37	79	39	93	Optical
50	31	82	29	76	Electrical
28	10	59	17	36	Magnetic
39	23	70	23	54	Dielectric
27	26	31	25	49	Nuclear
60	77	45	66	53	Chemical
46	59	37	68	29	Biological
46	17	60	56	33	Ceramics
60	43	67	74	64	Glasses and Amorphous Materials
37	11	76	11	61	Elemental and Compound Semiconductors
47	36	71	35	66	Inorganic, Non-Metallic Elements and Compounds
36	10	38	32	31	Ferrous Metals and Alloys
32	11	35	36	16	Non-Ferrous Structural Metals and Alloys
29	13	46	23	28	Non-Ferrous Conducting Metals and Alloys
73	93	57	78	55	Plastics
53	94	36	54	31	Fibers and Textiles
44	76	29	47	20	Rubbers
57	71	50	60	39	Composites
50	54	51	47	66	Organic and Organo-Metallic Compounds
51	43	71	46	71	Thin Films
66	85	47	67	54	Adhesives, Coatings, Finishes, Seals
35	51	27	32	25	Lubricants, Oils, Solvents, Cleansers
8	16	8	8	1	Prosthetic and Medical Materials
5	1	11	5	1	Plain and Reinforced Concrete
10	14	10	15	3	Asphaltic and Bituminous Materials
41	50	21	58	40	Wood and Paper

CONSUMER GOODS	Apparel and Textiles	Household Appliances - Electronic	Packaging and Containers	Printing and Photography	
37	11	59	34	44	Extraction, Purification, Refining
63	88	58	61	71	Synthesis and Polymerization
46	39	65	40	56	Solidification and Crystal Growth
35	6	45	30	12	Metal Deformation and Processing
56	68	54	58	27	Plastics Extrusion and Molding
49	45	47	50	35	Heat Treatment
38	25	45	28	31	Material Removal
52	60	52	49	25	Joining
36	21	42	31	25	Powder Processing
38	19	66	25	57	Vapor and Electrodeposition, Epitaxy
39	31	54	23	63	Radiation Treatment
54	39	61	42	55	Plating and Coating
49	38	64	31	79	Chemical
63	58	62	67	52	Testing and Non-Destructive Testing
20	10	22	35	13	Earth Sciences
50	55	50	50	58	Analytical Chemistry
60	71	60	60	68	Physical Chemistry
68	90	54	65	75	Organic and Polymer Chemistry
54	42	60	49	69	Inorganic Chemistry
56	44	76	49	75	Solid State Chemistry
55	48	81	46	71	Solid State Physics
56	39	67	68	43	Ceramics and Glass
65	84	54	67	59	Polymer Processing
20	11	26	19	17	Extractive Metallurgy
47	19	56	44	45	Metals and Inorganic Materials Processing
37	12	47	35	29	Physical Metallurgy
52	63	39	54	49	Chemical Engineering
50	51	47	50	32	Mechanical Engineering
42	35	77	29	42	Electronic Engineering
14	14	26	10	8	Aerospace Engineering
13	14	26	6	8	Nuclear Engineering
24	35	19	26	13	Bioengineering
32	39	23	45	17	Civil and Environmental Engineering

20 Consumer Goods (21)

***Durability: resistant polymers and rubbers; stronger plastics; strength and fatigue; corrosion resistance; coatings; wear resistance; reliability; life of household goods

*Mechanical properties: special viscoelastic properties of rubbers and plastics; brittleness of plastics

*Testing: evaluation

*Materials for Wankel engine; for steam operated engines

*Stovetops

*Thermoelectric materials

22 Furniture (11)

**Flammability, fire resistance

**Mechanical Properties: reinforced plastics; scratch resistance; high strength; cushioning; plastic with feel of wood; carbon fiber; particulate-filled materials

*Dirt resistant fabrics

*Ease of fabrication

23 Household Appliances—Electronic (28)

***Displays: liquid crystals; cathode structures for photo-emitters; picture tube life is too short; more efficient cathode luminescence; flat TV screen; solid state TV; new phosphors; solid state display; cheaper displays, e.g. electroluminescent or liquid crystal; brighter phosphors

**Recording: sound and video recording; processing discs

*LSI for consumer products; miniaturize circuits; interconnection technology

*Packaging: low cost; reduce damage

*Flammability; non-flammable plastics

*Surge and shock protection

*Impact resistant plastics

*Switching contacts

24 Household Appliances—Nonelectric (25)

***Corrosion; wear; fatigue; corrosion; life expectancy; low cost corrosion resistance; environmental resistant polymers

***Mechanical properties: shaping and forming; toughness; fabrication ease; impact resistance; composites; composite processing; thermoplastic composites

*Enamels; hot water tank coatings; self cleaning coatings for ranges

*Cost

*Thermoelectric refrigerators

*NDT for reliability

26 Packaging and Containers (51)

Properties

***Higher strength/weight: higher strength glass; higher strength can alloys; improved deep drawing aluminum alloys; improve wet strength of corrugated containers; better low temperature properties

***Recyclable containers: biodegradable containers; low cost reclamation processes

*Reduce permeability of packaging films

*Composites

*Blood and plasma packaging materials that are tough and inert

Materials

***Develop biodegradable packaging materials: better polymers; plastics; rubbers; high impact foams

***Glass: higher strength; impact resistance; high temperature properties of glass; physical chemistry of glass

*Wet strength of corrugated containers: fireproof paper; paper products

*Raw materials supply

Processes

***Better plastic containers; biodegradable; improved cross-linking; high temperature plastics; molecular architecture for special mechanical properties

***Glass processing

**Bonding, fastening

*Improve deep drawing of aluminum alloys

27 Printing and Photography (34)

***Photographic Emulsions: understanding of latent image process; finer grain emulsions; faster emulsions; new compositions; improved photographic papers; influence of morphology structure, surfaces on photographic activity; color printing; faster printing; effect of impurities on photocarrier traps; substitute for silver halides; substitute for silver, non-silver process; new materials; inexpensive light sensitive paper; erasable photographic materials; new photosensitive imaging materials

**Dry electrophotography; lower cost; improved photoconductor; semiconducting plastics; conducting plastics; cold cathode devices for electrophotography; photoelectronic materials with 2 eV gap

*Photochromic plastics; moldable photochromics; photochromic devices

*Colloid properties

*Ionic transport

*More flexible packing

Area 30 Defense and Space

Figure 5.4 indicates that highest priority should be given to Mechanical and Acoustic Properties and also to Chemical Properties, with Microstructure at the electron microscopic level receiving high rating. Composites and Adhesives are the materials which receive the highest rating. Testing and Joining are the processes which are most important. Aeronautical Engineering is the Discipline which stands out in this group.

In the area of Defense and Space, mechanical properties were emphasized, particularly materials with improved weight-to-strength ratios. This is reinforced under the area of Military Aircraft where composites and turbine blade materials, both of which are important for their mechanical properties, received many comments. The other topics which came in most strongly were again related to reliability and testing, corrosion, fatigue, and a variety of non-destructive testing methods, which should receive high priority for Applied Research. For Missiles the mechanical properties, particularly improved strength-to-weight ratio, were important. Joining and environmental stability were important here, and the special needs for improved heat shields and nose cone materials were emphasized. For Naval Vessels, mechanical properties again were high on the list with corrosion and protection against corrosion being important areas for research. Under the sub-area of Ordnance and Weapons, mechanical properties, particularly for lightweight armor, were important. Bonding and again protection against corrosion were important areas for further work. Under Radar and Military Communications, optical properties both for communications and for sensors received a high rating and reliability was also an important problem. Under the sub-area Spacecraft, high temperature mechanical properties received the highest rating. For Undersea Equipment, mechanical properties for deepsea vehicles received the highest priority along with an indication of a need for further research on corrosion resistance and environmental protection.

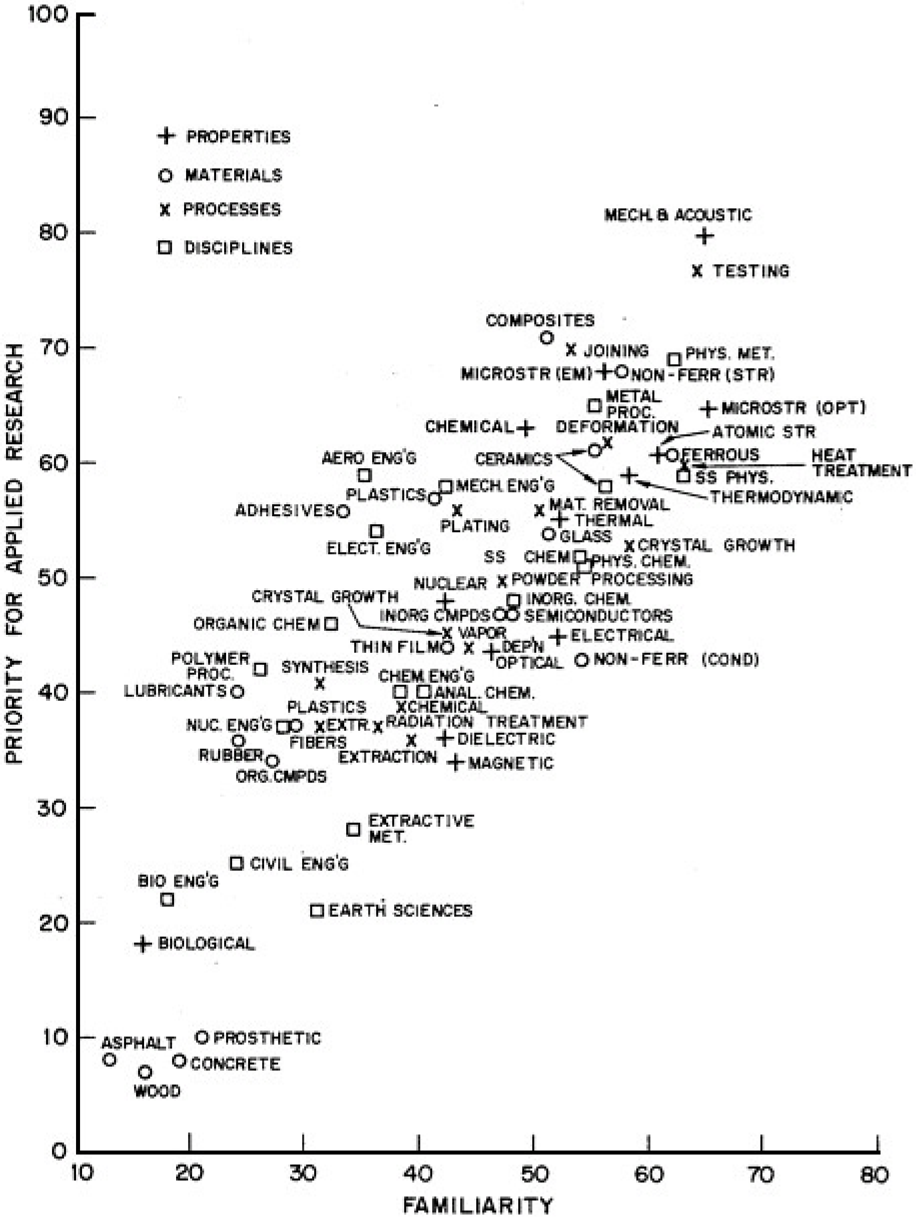

FIGURE 5.4 PRIORITY FOR APPLIED RESEARCH—AREA 30 DEFENSE AND SPACE

TABLE 5.13 Priority for Applied Research - Area 30 - Defense and Space

DEFENSE AND SPACE	Military Aircraft	Missiles	Naval Vessels	Ordnance and Weapons	Radar and Military Communications	Spacecraft	Undersea Equipment	
61	62	61	47	62	72	58	50	Atomic Structure
68	76	65	57	65	61	69	64	Microstructure (Electron Microscope Level)
65	71	62	53	69	56	65	63	Microstructure (Optical Microscope Level)
59	61	70	49	54	56	62	48	Thermodynamic
55	51	63	29	55	59	69	41	Thermal
80	90	75	79	80	54	85	85	Mechanical and Acoustic
44	25	47	23	54	78	46	28	Optical
45	22	38	30	45	93	44	32	Electrical
34	15	28	25	32	63	27	40	Magnetic
36	15	29	27	38	73	30	39	Dielectric
48	29	59	30	56	61	54	33	Nuclear
63	72	54	57	69	39	62	78	Chemical
18	11	10	23	16	18	20	25	Biological
61	57	60	29	60	59	72	60	Ceramics
54	45	45	30	52	64	64	60	Glasses and Amorphous Materials
47	25	42	32	48	69	48	27	Elemental and Compound Semiconductors
47	38	47	32	48	67	48	26	Inorganic, Nonmetallic Elements and Compounds
61	64	55	63	75	37	57	79	Ferrous Metals and Alloys
68	78	67	65	70	25	75	80	Nonferrous Structural Metals and Alloys
43	32	35	36	47	45	45	51	Nonferrous Conducting Metals and Alloys
57	61	57	49	62	42	63	50	Plastics
37	37	39	30	31	20	54	27	Fibers and Textiles
36	40	33	35	36	17	34	43	Rubbers
71	64	76	55	71	39	79	68	Composites
34	29	31	33	34	37	35	25	Organic and Organo-Metallic Compounds
44	31	39	32	41	70	45	23	Thin Films
56	66	54	52	56	29	63	54	Adhesives, Coatings, Finishes, Seals
40	38	31	33	35	21	47	38	Lubricants, Oils, Solvents, Cleansers
10	4	7	14	9	5	10	11	Prosthetic and Medical Materials
8	1	5	17	6	7	1	19	Plain and Reinforced Concrete
8	2	8	22	7	5	1	14	Asphaltic and Bituminous Materials
7	2	4	12	6	7	1	5	Wood and Paper

DEFENSE AND SPACE	Military Aircraft	Missiles	Naval Vessels	Ordnance and Weapons	Radar and Military Communications	Spacecraft	Undersea Equipment	
36	29	28	33	32	47	35	31	Extraction, Purification, Refining
41	37	37	31	47	45	42	27	Synthesis and Polymerization
53	52	39	41	57	78	44	45	Solidification and Crystal Growth
62	76	54	56	71	30	66	70	Metal Deformation and Processing
37	38	32	35	45	25	40	38	Plastics Extrusion and Molding
60	71	53	56	67	45	62	64	Heat Treatment
56	69	51	47	54	43	60	50	Material Removal
70	81	65	70	64	51	76	78	Joining
50	60	46	34	55	40	51	35	Powder Processing
44	34	42	25	43	74	45	25	Vapor and Electrodeposition, Epitaxy
37	22	31	19	42	71	40	21	Radiation Treatment
56	61	53	49	56	48	58	53	Plating and Coating
39	27	36	29	44	64	38	26	Chemical
77	87	75	63	75	68	81	73	Testing and Nondestructive Testing
21	11	19	17	14	19	22	36	Earth Sciences
40	36	36	27	46	42	42	32	Analytical Chemistry
52	45	54	45	56	54	53	45	Physical Chemistry
46	44	48	40	50	35	51	42	Organic and Polymer Chemistry
48	41	49	39	47	53	50	42	Inorganic Chemistry
53	43	52	37	57	80	50	41	Solid State Chemistry
59	49	57	36	64	87	55	52	Solid State Physics
58	52	54	34	59	68	61	63	Ceramics and Glass
42	44	49	31	43	20	47	42	Polymer Processing
28	30	22	28	27	24	26	33	Extractive Metallurgy
65	76	60	55	75	51	59	58	Metals and Inorganic Materials Processing
69	78	67	65	78	48	70	67	Physical Metallurgy
40	38	39	38	46	30	41	36	Chemical Engineering
58	65	56	50	69	39	56	58	Mechanical Engineering
54	45	57	39	53	77	55	40	Electronic Engineering
59	72	74	25	50	46	74	24	Aerospace Engineering
37	24	43	35	42	32	42	31	Nuclear Engineering
22	15	12	29	13	19	33	21	Bioengineering
25	21	19	28	21	17	24	33	Civil and Environmental Engineering

30 Defense and Space (61)

***Mechanical properties; strength and fatigue; lighter weight armor; high strength; lighter weight-strength; gun hard materials; ceramets; high strength fibers and plastics, composites

**Lasers: high energy lasers; growth of laser crystals; tuneable lasers; high power lasers

**Energy sources; more efficient; atomic energy; coal; solar energy

**Heat resistance; high temperature strength; high temperature materials

**Corrosion: high temperature oxidation; stress corrosion; chemical attack (oxidation, corrosion)

**Radiation damage resistant electronics; degradation of LED’s due to ionization enhanced diffusion; ion implantation; degradation due to high energy radiation

*Optical communications; modulators; electro-optic

*Applications in reconnaissance; optical; infrared imagings

*Windows; laser windows; infrared windows

*Sonar

*Radome materials

*Deep submergence structures

* Adhesion; adhesion mechanisms

*Reliability: long life guidance systems; improve reliability

*Miniaturization

31 Military Aircraft (110)

***Composities: develop composites; structural design for composites; improved fracture toughness of composites; low cost composites; weldable composites; high-performance composites; high strength fiber composites; high temperature composites; FOD resistant composites; dispersion hardened alloys; reliability of composites

***Turbine blades: superalloy development; high temperature materials for turbines; turbine blades-solidification; high temperature resistance; develop superalloys; high temperature high strength alloys; gas turbine parts; high temperature alloys; powder methods for superalloys; superalloy powders; ceramics which resist catastrophic failure; dynamic/static properties of limited ductility materials

***Corrosion; surface protection; stress corrosion; environmental degradation; degradation of joints; high temperature coatings; erosion resistance; bearing service life

***Non destructive testing: NDT for bonds; NDT is Achille's heel; failure analysis; catastrophic failure; behavior in service; on-line NDT; service life; NDT and failure prediction; methods to anticipate failure; NDT of ceramics

***Fatigue: prevention of fatigue; fatigue analysis; improved fatigue properties; fatigue crack growth rate; understand crack propagation; fatigue and corrosion fatigue; fatigue prevention; fatigue of airframes; fatigue at elevated temperatures

**Strength/Weight: high strength, light alloys; lightweight, high temperature alloys; high strength/weight

**High Temperature Alloys: coatings; microstructural stability; creep resistance

**Welding: welding of titanium; weldable aluminum alloys; welding of dispersion hardened metals

**Fracture toughness, light armor, impact resistance

*Powder metal forgings; alloy powders

*Adhesives, fabrication of metal-nonmetal systems

*Low cost material removal; processing; low cost processing

*Reliable solid state components

*Displays

*Magnets
*Laser windows

32 Missiles (50)

***Improved heat shields; nose cone materials; materials for nozzles and leading edges; erosion resistant materials for reentry; materials for nose cone; high temperature capability; nose tips; heat shields, high temperature materials; reentry ablation materials

***High strength/weight; high strength; light weight; strength/weight; higher strength; higher strength-to-weight; weight reduction; stronger, light weight

**Joining: integrity of polymeric adhesives; degradation of adhesive bonds; adhesive-mechanical joints; adhesive bonds; welding

*Environmental degradation; resistance to environment; hydrogen compatibility; storage life; radiation resistant semiconductors

33 Naval Vessels (40)

***Corrosion: effects of salt water environment; corrosion; corrosion resistance; stress corrosion cracking; environmental degradation of resin-bonded composites; environmental degradation of adhesive bonds; stress corrosion cracking; stress corrosion; pitting corrosion

***Higher strength to weight; superstrength plastics for superstructures; materials for lightweight structures; fabrication of lightweight structures; lightweight materials; high strength; lighter materials for submarines; composites for ship construction

**Coating: to reduce corrosion; low drag and low contamination paints; antifouling coatings; new surface materials to reduce water flow force

**Detection: better emitting materials; superconducting magnetometers for detection; sonar ceramics; materials for acoustic and EM detectors

**Sound absorbing coatings; radar absorbing materials; non-magnetic structural materials; non-magnetic materials

**Mechanical properties: fracture toughness; impact resistance; fatigue and crack propagation; tough and crack resistant

*New propellor materials; propellors to withstand cavitation

*Bonding and fastening

*Semiconducting motors for ship operation

*NDT for welding

34 Ordnance and Weapons (62)

***Improved strength/weight materials; composites; light armor
**Corrosion; shelf life; marine environment corrosion
*Adhesives; joining
*Radiation hard components
*Wear resistance
*Windows for lasers
*IR imaging devices
*Fatigue resistance
**Bonding: room temperature curing adhesive; durability of adhesives; degradation of bonds
*NDT for residual life
*Degradation during storage
*Armor, ballistic protection

35 Radar and Military Communications (69)

***Optical: photoelectric detectors; infrared detectors; materials for detectors; optical communication; IR and UV seeking materials; optical sensors; IR detectors; windows: for lasers; for IR windows; lasers: improved laser materials; solid state lasers; efficient lasers; IR injection lasers; modulators: optical modulators; IR modulators; laser modulators; integrated optics; transmission: waveguides; fibers for optical transmission; low loss optical materials

***Reliability: environmental deterioration; degradation failure mechanisms; response to severe environmental degradation of adhesives; materials to withstand salt water; reliable bonding and packaging; volatility in storage

**Microwave sources; solid state microwave devices; GaAs for microwave sources; array radars

*Biodegradable packaging

*Size and weight reduction

*High susceptibility

*Electron emitters

*Bonding composites

*High temperature performance

*High strength plastics

*Acoustic surface wave devices; surface wave acoustic devices

*Integrated circuits; yields

*Superconductors

*Radiation resistant materials

*Acoustic delay lines

*Acoustic transducers

36 Spacecraft (57)

Properties

***High temperature ablation resistance; reentry protection; high temperature structural properties
**Low flammability
**Hydrogen compatibility; radiation resistance; stable in vacuum
**High weight/strength

Materials

***Thermal control coatings; high temperature coatings
**Composites
Processes
**Testing

37 Undersea Equipment (51)

***Materials for deepsea vehicles; deep submergence hulls; equipment for ocean bed mining; materials for pressure of ocean depths; pressure hull materials; undersea equipment; pressure vessels; compression properties; effect of hydrostatic pressure on mechanical properties; processing of large spheres; getting leads through pressure vessels; more inert structural materials for deepsea

***Corrosion resistance; corrosion of metals; corrosion protection; stress corrosion cracking; corrosion resistance; stress corrosion; environmental protection

**Mechanical properties: strength, design criterion for brittle materials; fatigue; fracture properties; strength/weight; strength to density

**Improved transducer; transducer technology; acoustic transport in sea water; sonar equipment

**Seals for repeaters; weldable materials; welding thick sections; welding and joining; joining methods for brittle materials; cements, sealants for deepsea equipment

*NDT to avoid catastrophic failure

*High intensity lights

*Undersea cable design

*Propulsion systems

Area 40 Energy

The data in Fig. 5.5 indicate that Chemical Properties are the most important in the Energy area. This relates to a variety of properties under this general heading, such as the burning of fossil fuels, batteries and fuel cells, as well as corrosion and environmental stability. Mechanical and Acoustic Properties, Microstructure at the Electron Microscopic Level, Thermal Properties and Nuclear Properties were also important. Materials important for their structural properties received the highest ratings, such as Non-ferrous Structural Materials, Composites, and Adhesives. Testing was the most important Process but Joining and Plating were also given high priority. The Disciplines Solid State Chemistry, Physical Metallurgy, Ceramics, Metal Processing, Mechanical Engineering, Nuclear Engineering, and Chemical Engineering were all important to this area.

The general comments on the area of Energy indicate the future importance of superconductors, and solar energy with improved batteries and improved high temperature materials also being important. Under the sub-area of Batteries and Fuel Cells improved Materials for solid state electrolytes, improved catalysts and improved seals received high priority. For Direct Conversion of energy, solar cells came in for the highest priority. In the sub-area of Electric Transmission and Distribution superconductors should receive high priority for transmission media of the future. Improved electrical insulation received many comments. Under Fuel Transmission and Distribution, mechanical properties came in for the highest priority particularly in regard to pipeline materials. For Nuclear Reactors, the important area requiring further development was the control of radiation damage and the protection of the fuel elements from their environment and vice versa. Under Thermonuclear Fusion the greatest materials problems were related to the stability of materials under high neutron fluxes. For Turbines and Generators improved mechanical properties particularly at high temperatures are needed for improved high temperature operation.

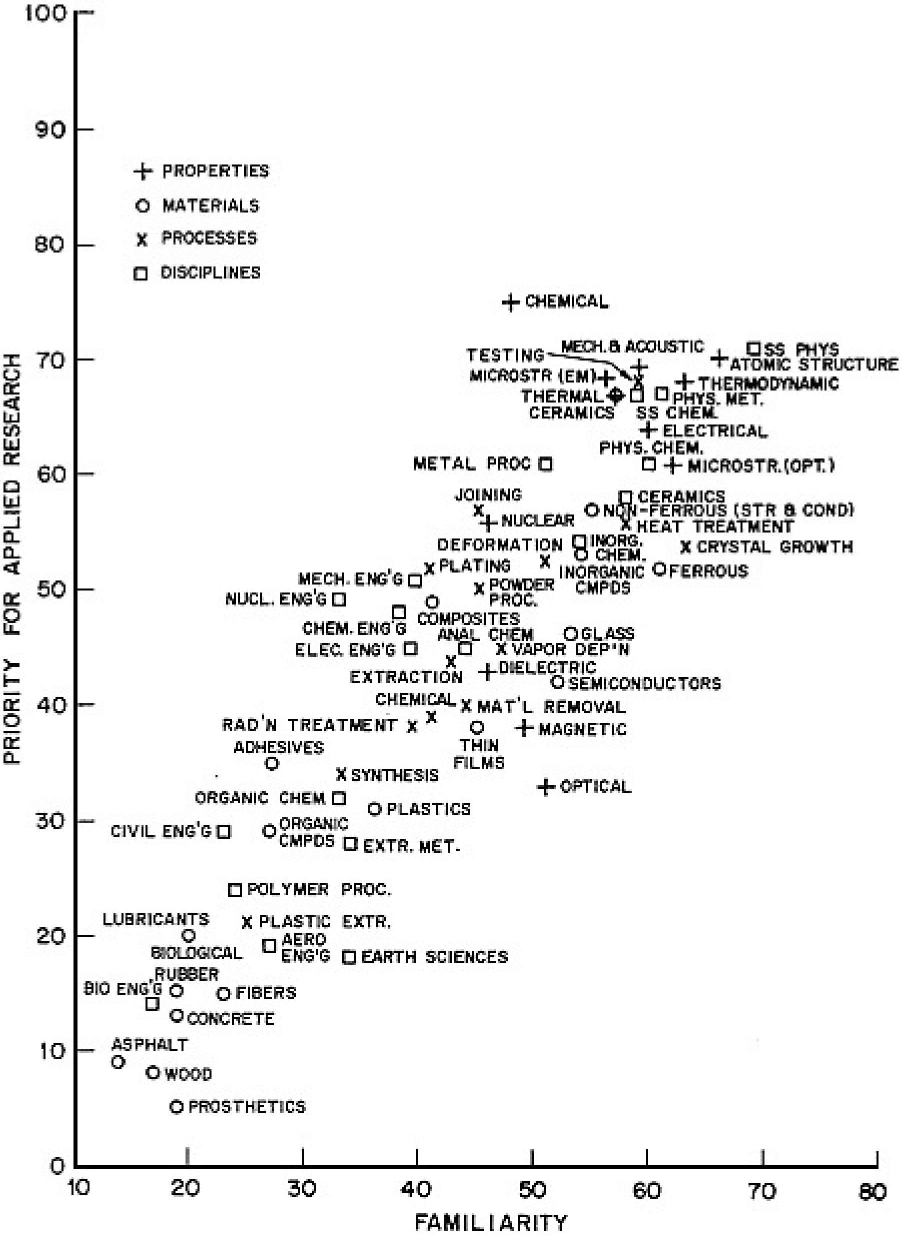

FIGURE 5.5 PRIORITY FOR APPLIED RESEARCH—AREA 40 ENERGY

TABLE 5.14 Priority for Applied Research - Area 40 - Energy

ENERGY	Batteries and Fuel Cells	Direct Conversion	Electric Transmission and Distribution	Nuclear Reactors	Thermonuclear Fusion	Turbines and Generators	
70	65	75	65	79	80	63	Atomic Structure
68	60	64	66	79	76	75	Microstructure (Electron Microscope Level)
61	57	57	48	70	62	75	Microstructure (Optical Microscope Level)
68	73	73	67	65	64	68	Thermodynamic
67	57	84	73	67	74	62	Thermal
69	42	55	59	89	83	88	Mechanical and Acoustic
33	25	73	30	24	45	17	Optical
64	83	89	90	32	59	39	Electrical
38	29	40	64	23	51	28	Magnetic
43	51	57	66	21	47	25	Dielectric
56	41	53	31	92	89	28	Nuclear
75	95	65	43	81	67	76	Chemical
18	25	16	7	25	21	1	Biological
67	66	70	51	69	72	77	Ceramics
46	51	57	54	35	53	37	Glasses and Amorphous Materials
42	50	75	46	26	35	17	Elemental and Compound Semiconductors
53	70	64	46	41	56	41	Inorganic, Non-Metallic Elements and Compounds
52	26	31	46	77	52	72	Ferrous Metals and Alloys
57	35	36	43	79	75	76	Non-Ferrous Structural Metals and Alloys
57	54	52	80	46	67	52	Non-Ferrous Conducting Metals and Alloys
31	42	26	38	21	23	27	Plastics
15	20	10	18	9	10	18	Fibers and Textiles
15	23	6	19	9	7	12	Rubbers
49	42	48	47	45	47	72	Composites
29	44	34	39	14	19	24	Organic and Organo-Metallic Compounds
38	47	65	54	16	28	25	Thin Films
35	35	36	37	30	25	49	Adhesives, Coatings, Finishes, Seals
20	9	13	19	21	13	42	Lubricants, Oils, Solvents, Cleansers
5	9	8	2	3	3	3	Prosthetic and Medical Materials
13	4	6	10	10	17	7	Plain and Reinforced Concrete
9	11	6	11	11	3	4	Asphaltic and Bituminous Materials
8	9	5	21	4	2	4	Wood and Paper

ENERGY	Batteries and Fuel Cells	Direct Conversion	Electric Transmission and Distribution	Nuclear Reactors	Thermonuclear Fusion	Turbines and Generators	
44	39	50	50	43	45	32	Extraction, Purification, Refining
34	38	44	46	22	19	34	Synthesis and Polymerization
54	56	66	54	41	48	66	Solidification and Crystal Growth
53	28	35	55	67	64	78	Metal Deformation and Processing
21	25	21	28	15	15	20	Plastics Extrusion and Molding
56	33	45	59	67	63	74	Heat Treatment
40	26	36	26	45	45	70	Material Removal
57	42	51	45	72	63	73	Joining
50	50	47	41	53	48	65	Powder Processing
45	50	68	50	28	49	39	Vapor and Electrodeposition, Epitaxy
39	26	57	37	49	53	21	Radiation Treatment
52	50	52	51	46	55	64	Plating and Coating
39	52	53	39	28	36	26	Chemical
68	53	62	58	84	76	78	Testing and Non-Destructive Testing
18	14	23	19	17	16	12	Earth Science
45	56	43	38	47	45	39	Analytical Chemistry
61	79	61	52	57	59	52	Physical Chemistry
32	43	36	40	23	23	24	Organic and Polymer Chemistry
54	73	59	48	47	50	45	Inorganic Chemistry
67	79	75	70	63	67	47	Solid State Chemistry
71	71	85	83	70	79	50	Solid State Physics
58	59	64	54	55	57	64	Ceramics and Glass
24	26	24	35	16	17	25	Polymer Processing
26	16	23	32	34	30	28	Extractive Metallurgy
61	46	52	63	67	63	79	Metals and Inorganic Materials Processing
67	48	48	69	82	76	81	Physical Metallurgy
48	54	40	34	56	57	38	Chemical Engineering
51	30	47	40	59	55	74	Mechanical Engineering
45	44	64	61	32	45	31	Electronic Engineering
19	14	24	12	14	17	32	Aerospace Engineering
49	23	46	21	87	85	29	Nuclear Engineering
14	15	12	13	17	12	6	Bioengineering
29	14	29	27	39	36	24	Civil and Environmental Engineering

40 Energy (56)

**Superconductors; high T_c; improved SC systems; room temperature SC's; transmission with SC's; SC cables

**Batteries: energy storage; batteries for electric autos; electrodes for batteries; high density, low cost, low weight batteries; long life; better electrolytes

**Solar energy: photovoltaic conversion; solar energy converters

**High temperature materials: for gasification of coal; tubing for high temperature reactors to convert coal/oil to gas

*Combustion efficiency; sulphur emission from burning coal and oil

*Improved electrical transmission; efficient distribution

*Radiation resistance

*Welds with fracture toughness

*Thermal pollution

*Power from tides

*Transport of oil; gas

*MHD conversion

*NDT for lifetime prediction; failure criterion

*Fuel cells

*Creep; creep and fatigue

*Laser materials

41 Batteries and Fuel Cells (139)

Properties

***Better electrodes: more reversible; mechanical and chemical stability; longer life; corrosion resistance; lightweight; higher efficiency

**Separators: thinner; more porous; more stable
**Higher energy density: smaller; high storage/weight; low weight
Materials
***Solid state electrolytes: improve conductivity; light weight
**Catalysts: efficient; low cost; non-fouling
**Fuel cell containers: electrodes
*Solar cells: cost; organic materials
*New battery materials; systems
*New container materials

Processes

***Seals, vapor tight

42 Direct Conversion (93)

***Solar energy: large area, efficient solar cells; higher efficiency; more efficient photovoltaic cells; better conversion devices; low cost; junction fabrication for solar cells; cost; efficiency; optical properties of surfaces; converters for radiant energy; efficiency and stability; heat mirrors for conversion; degradation of solar cells; efficiency growth of Si for solar cells; high efficiency; cost CdS, Cd S-Cu solar cells; solar lasers

**Thermoelectric power converters; better efficiency than bismuth-telluride; thermoelectric efficiency; high temperature thermoelectronics

**Radioactive-electric converter; fast breeder reactors; fusion reactors; radiation containers; materials for 1000–1500°C reactors; reliable materials for fast breeder reactors

**MHD converters: high temperature materials for MHD; MHD ducts; electrodes for EHD

**High temperature materials; high temperature properties for plasma containment

**Corrosion

*Superconductors: for rotary generators; for underground transmission; for electric generators

*Energy storage: more efficient; batteries; storage of thermal energy

*Geothermal wells: drilling materials; heat exchangers

*Improved thermal insulation

*Low work function emitters; thermionic emission

*Efficient turbines

43 Electric Transmission and Distribution (86)

***Superconductors: for power transmission; T_c>25°K; higher T_c; T_c>18°K; for underground transmission; superconducting magnetic materials for suspension and propulsion; high I_c; pure niobium; new superconductors; low cost superconducting cables; low loss superconducting transmission lines; superconducting AC to DC converters; handling of liquid He II; large scale cryogenic technology; cryogenic thermal insulation; cryogenic pipelines

***Insulation for underground cables; ceramic spacers for cables; insulating materials for superconducting cables; better insulators; low loss insulators; purification of refractory ceramics; high voltage breakdown; replace cellulose paper with polymeric materials in EHV cables; insulation for HV transformers

**Light weight conductors; higher purity metal conductors; low-loss transmission lines; high conductance/weight; lower cost

**AC/DC converters; more efficient turbines; solid state rectifiers for high voltage conversion

**Corrosion for Al conductors; corrosion reducing coatings for HV cables; corrosion resistance for underground cables

*Transformer cores; low loss magnetic materials

*Solid state electric meters

*More efficient circuit breakers

44 Fuel Transmission and Distribution (13)

***Mechanical properties: high strength, toughness, notch sensitivity, fracture propagation
**Corrosion
**Non-destructive testing
*Weldability of pipeline steels

45 Nuclear Reactiors (121)

***Radiation damage; structural damage; creep; swelling; void formation
**Coatings and cladding of fuel elements; lightweight; radiation damage resistant cladding
**High temperature materials; corrosion resistant at high temperatures; radiation resistant at high temperatures
**Corrosion; stress corrosion; radiation effects on corrosion
*Non-destructive testing methods for reactor components
*Welding; improved methods; reliability of welds
*Liquid metals; properties of liquids, containment of liquids
*Fuel elements, new fuels; fuels for breeder reactors
*Nuclear waste disposal; environmental effects
*Safety; radiation-hard control equipment

46 Thermonuclear Fusion (57)

***Radiation damage, container problems; stability under high neutron fluxes, blistering, void formation

**High temperature properties, for containers, for converters

**Superconductors: for containment magnets, higher Tc; for plasma confinement; for cables for magnetic containment

*Heat exchange media; liquid metals

*Corrosion, of heat exchange piping

*Containment of tritium

*Hydrogen embrittlement

*Lasers and laser windows

47 Turbines and Generators (89)

***High temperature materials for turbines; 2500°F blade materials; eutectics; 2500°F to 3000°F rotor and stator blade operation; high temperature strength, ductility, fatigue resistance; corrosion resistance; refractory materials; ceramics, designs for brittle materials; develop structural ceramics; ceramic compounds; processing of ceramics, better hot strength ceramics

**Corrosion of turbine blades; oxidation resistant alloys; corrosion resistance; oxidation and hot corrosion; corrosion of superalloys; coatings; stability

**Mechanical properties, higher strength; creep resistance; higher strength/ weight; toughness

**Seals; metal seals, 2500°F seals; high temperature seals

*Testing; tests for reliability; to permit use of brittle materials

*Bearings; 2500°F bearings; wear; high temperature lubricants

*Superconductors: brushes for superconducting machinery; superconducting materials; higher T_c

*Magnets; improved magnetic properties

*Materials for cryogenic operation

*Improve silicon iron

Area 50 Environmental Quality

The Chemical and Biological properties stand out as being important in Fig. 5.6 for Environmental Quality. Plastics and Organic Compounds are the most important materials. Extraction is the process of outstanding importance, with the disciplines Chemical Engineering and Civil and Environmental Engineering being most important. As the overall comments on environmental engineering indicate, there are important needs for improved extraction methods which are also less polluting and as well as for increased recycling of materials. Health hazards from handling materials also received comment. Under the sub-area Mining and Raw Materials Extraction, the pollution of the environment was also a major concern, and an important area for further work. Improved methods of treating ores and extracting minerals from ores are necessary to improve the efficiency of mining and extraction operations. Under Pollution, the primary emphasis was on catalysis, particularly for automobiles, with further improvements in pollution detectors also being required. Under Recycling and Solid Waste Disposal, biodegradability, improved waste disposal along with the use of materials that are recyclable are important. Emphasis should also be given to development of new uses for waste materials and for separation of waste materials into reusable products. Under Reliability, Safety and Maintainability, safety received high priority, and again, Testing and Non-Destructive Testing are very important. And of course reliability, corrosion and fatigue are also important in this area. Under Substitution Opportunities there are a few suggestions for detailed reuse such as processing of fly ash but in general the responses indicate that detailed investigation of substitution opportunities need to be examined with the particular material and use in mind. Under the sub-area of Working Conditions, noise is a form of pollution causing considerable concern, and safety hazards are ubiquitous.

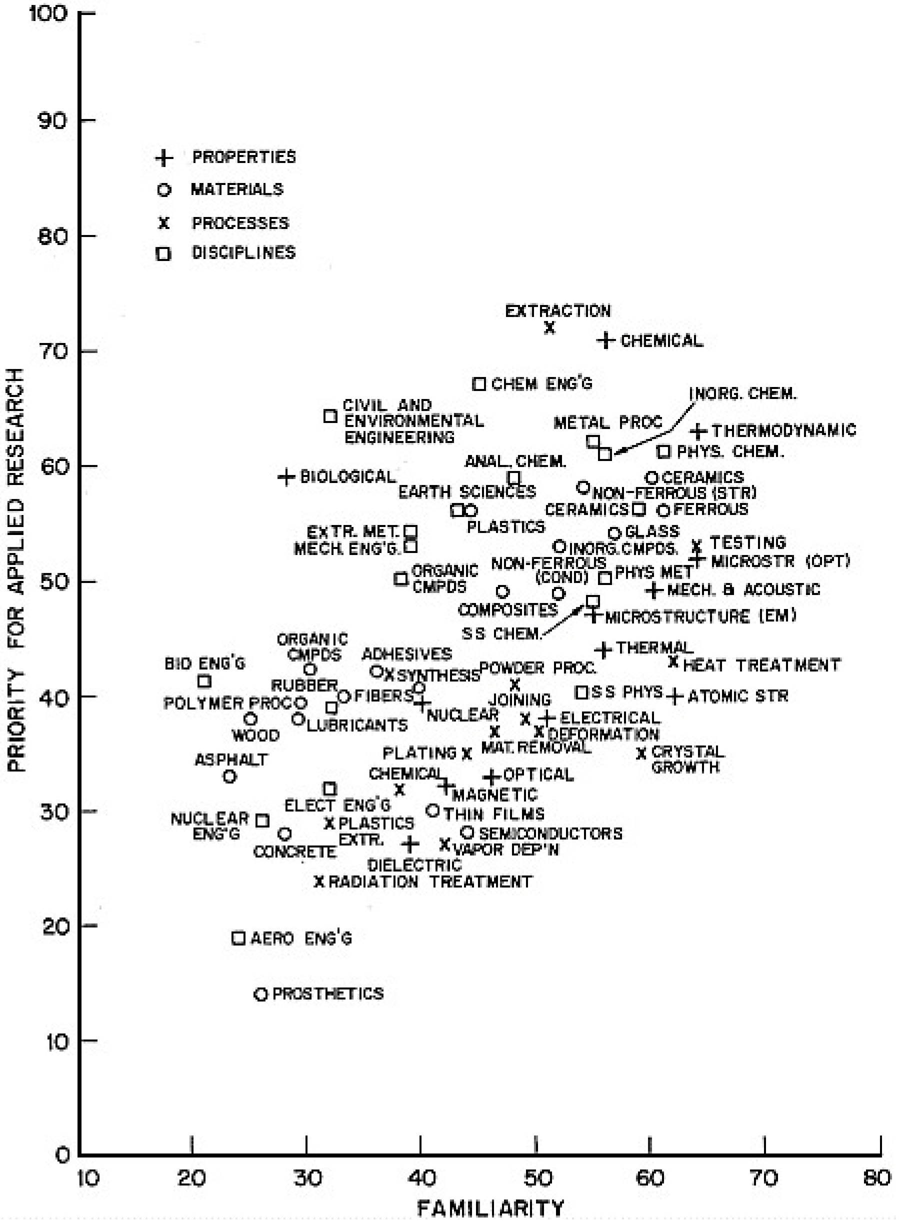

FIGURE 5.6 PRIORITY FOR APPLIED RESEARCH—AREA 50 ENVIRONMENTAL QUALITY

TABLE 5.15 Priority for Applied Research - Area 50 - Environmental Quality

ENVIRONMENTAL QUALITY	Mining and Raw Materials Extraction	Pollution	Recycling and Solid Waste Disposal	Reliability, Safety, Maintainability	
40	37	43	29	54	Atomic Structure
47	43	50	34	70	Microstructure (Electron Microscope Level)
52	56	47	42	66	Microstructure (Optical Microscope Level)
63	67	62	63	55	Thermodynamic
44	42	45	40	54	Thermal
49	50	36	46	87	Mechanical and Acoustic
33	24	40	23	44	Optical
38	33	44	28	53	Electrical
32	35	30	28	46	Magnetic
27	27	30	19	38	Dielectric
39	34	52	27	43	Nuclear
71	72	78	68	79	Chemical
59	34	62	70	56	Biological
59	62	58	55	69	Ceramics
54	40	53	62	68	Glasses and Amorphous Materials
28	23	32	16	52	Elemental and Compound Semiconductors
53	53	57	50	49	Inorganic, Nonmetallic Elements and Compounds
56	60	44	64	69	Ferrous Metals and Alloys
58	61	46	64	71	Nonferrous Structural Metals and Alloys
49	44	42	52	55	Nonferrous Conducting Metals and Alloys
56	29	52	70	70	Plastics
40	15	36	49	55	Fibers and Textiles
39	23	30	51	53	Rubbers
49	34	41	53	77	Composites
42	30	48	39	40	Organic and Organo-Metallic Compounds
30	17	39	19	54	Thin Films
42	32	42	34	70	Adhesives, Coatings, Finishes, Seals
38	27	37	37	47	Lubricants, Oils, Solvents, Cleansers
14	10	6	7	49	Prosthetic and Medical Materials
28	24	16	33	46	Plain and Reinforced Concrete
33	23	26	39	40	Asphaltic and Bituminous Materials
38	14	33	55	34	Wood and Paper

ENVIRONMENTAL QUALITY	Mining and Raw Materials Extraction	Pollution	Recycling and Solid Waste Disposal	Reliability, Safety, Maintainability	
72	83	71	80	42	Extraction, Purification, Refining
42	31	46	42	40	Synthesis and Polymerization
35	45	37	31	35	Solidification and Crystal Growth
37	32	25	39	63	Metal Deformation and Processing
29	19	21	34	45	Plastics Extrusion and Molding
43	36	38	45	63	Heat Treatment
37	39	34	38	47	Material Removal
38	36	31	35	68	Joining
41	42	39	38	57	Powder Processing
27	27	34	14	36	Vapor and Electrodeposition, Epitaxy
24	17	35	14	34	Radiation Treatment
35	31	43	25	54	Plating and Coating
32	28	45	24	39	Chemical
53	53	47	45	88	Testing and Nondestructive Testing
56	74	49	54	32	Earth Sciences
59	52	65	62	47	Analytical Chemistry
61	60	70	60	47	Physical Chemistry
50	34	57	53	58	Organic and Polymer Chemistry
61	69	68	60	46	Inorganic Chemistry
48	47	52	43	56	Solid State Chemistry
40	38	46	34	35	Solid State Physics
56	48	53	64	57	Ceramics and Glass
39	21	34	46	50	Polymer Processing
34	80	39	59	27	Extractive Metallurgy
62	71	51	64	66	Metals and Inorganic Materials Processing
50	57	39	47	66	Physical Metallurgy
67	72	65	68	60	Chemical Engineering
53	54	43	54	71	Mechanical Engineering
32	30	32	23	59	Electronic Engineering
19	13	17	14	42	Aerospace Engineering
29	26	31	20	45	Nuclear Engineering
41	16	46	45	58	Bioengineering
64	53	68	68	59	Civil and Environmental Engineering

50 Environmental Quality (32)

***Improve extraction methods, catalytic converters, improve incineration; convert or destroy pollutants; methods to dispose of old cars

***Standards: higher air quality standards; water quality; effects on ocean; land pollution

***Recyclability: recover wastes, use substitutes, biodegradability; recover metals

**Health hazards: handling corrosive materials; safety and health of personnel in collection; handling of dusty raw materials; silicosis; poisons

*Reduce noise

*Sensors for pollutants

51 Mining and Raw Materials Extraction (55)

***Pollution of air, land and water should be reduced; methods to eliminate pollution from pyrometallurgical operations; non-polluting methods, nature preserving mining techniques, minimize environmental degradation; means to make open pit mining ecologically acceptable

***Improve methods of treating low grade ores; aggregation; shortage of rich ores; beneficiation of low grade ores

***Improve extraction methods; one step processing; chemical mining; Al from ores other than Bauxite; removal of Fe from Cu ore; extraction of TiO_2 and Al_2O_3; better controls on existing methods; use of solid state reactions for ore conversion; in-situ

**Ore reserves; depletion of ore bodies is a problem; alternate sources for Al, fossil fuel resources

**Use of tailing; disposal of tailings; recycle tailings; recovery of metals from slag

*Processing equipment: corrosion, abrasion, for hydrometallurgical extraction

*Refractories; for gasification plants, to hold liquids at 2000°C, for pyrometallurgical processing

*Safety: remote control systems to improve mine safety

52 Pollution (90)

***Catalysts for automobile exhausts; design of converters, new catalytic materials; cheaper catalysts

**Pollution detection devices and systems for air and water; remote sensors; laser-based detectors

**Biodegradable plastics

*Recycling, glass, secondary uses

*Extractive processes; cleaner methods; improved methods to get sulphur not SO_2 from sulphide ores; reduce fluoride fumes from steel manufacturing; scrubbers for HCl; recovery of Hg, Cd, Pb; Cl_2 fumes; dust; heavy metal discharge

53 Recycling and Solid Waste Disposal (115)

Properties

***Biodegradability: recyclability; recyclable polymers; choose recyclable materials
**Economics
Materials
***Develop new uses for materials: polymers as fuels; garbage as fertilizer; new uses of glass; construction applications
*Recycle aluminum; tin; auto scrap; glass

Processes

***Sorting mechanisms: separation procedures; recovery of scrap; chemical separation methods
**Sewage disposal; rubbish collection; disposal systems
**Characterization: alloy analysis
**In-plant recycling; recycling of rejects
*Recovery of SO_2
*Recovery of elements; metals

54 Reliability, Safety, Maintainability (34)

***Safety: safety glass; eye protection; flammability; toxicity; designs for safety

***Testing: NDT in automotive industry, automated NDT worming devices; automated sensors; NDT of automobile components; NDT of materials to usage; reproducibility of properties

**Fatigue: corrosion fatigue; fatigue gauge to predict life

**Maintainability: maintenance sensors; design for maintenance integrity

**Design for brittle materials

**Corrosion; stress corrosion

*Wear

*Flammability; flame retardants for carpets, etc.

*Pollutants; low pollution deicants; catalytic converters

55 Substitution Opportunities (22)

***Reuse: process fly ash; replace problem materials; replace materials that require polluting processing; recycled materials for building

**Replacement: use polymers; synthetic paper; replace Pt catalysts; develop high temperature organics; composites: to replace metals; to replace alloys; graphite-structural composites; plastic-metal composites; use Co to replace Ni

**Degradation: coatings; design for longevity; “performance-environment” standards are needed

*Energy expenditure in processing

*Disposal of industrial liquid wastes

56 Working Conditions (9)

***Noise: materials to eliminate rolling noises; vibration absorption; muffler materials for transportation; appliances; tools; materials to absorb and dissipate airborn noises; materials to reduce noise pollution; cheaper noise level dosimeter

**Safety: Hazardous gases; improve performance of safety devices; materials to reduce hazards of fire and explosions in coal mines

Area 60 Health Services

Under the area of Health Services, Biological Properties were outstanding and Chemical Properties were also rated high as areas for further applied research. Prosthetic Materials, not surprisingly, received a very high rating; Plastics, Adhesives, Composites, and other Organic Compounds also rated high. Testing was again considered to be very important and Plastics Extrusion was considered to be an important process in this area. The Discipline of Biological Engineering received a very high rating and Organic Chemistry was also highly rated.

Overall comments on the area of Health Services stressed the importance of a variety of implant materials with extensive research on the biophysical aspects of materials being a major area for future effort. Under Artificial Organs, biocompatibility and the problems associated with the introduction of prosthetic materials into the body were very important. Many comments were made on the need for good artifical membranes. Under Medical Electronics improved sensors for monitoring body functions are needed. Under Medical Equipment there were also several comments on a variety of implant materials. Improved methods for the preservation of blood and organs are needed. Under the sub-area of Prosthetic Devices, the interface between the prosthetic materials and the body and the related problems of compatibility and rejection deserved highest priority. The problems of degradation and of the stability of implants in the body were also very important.

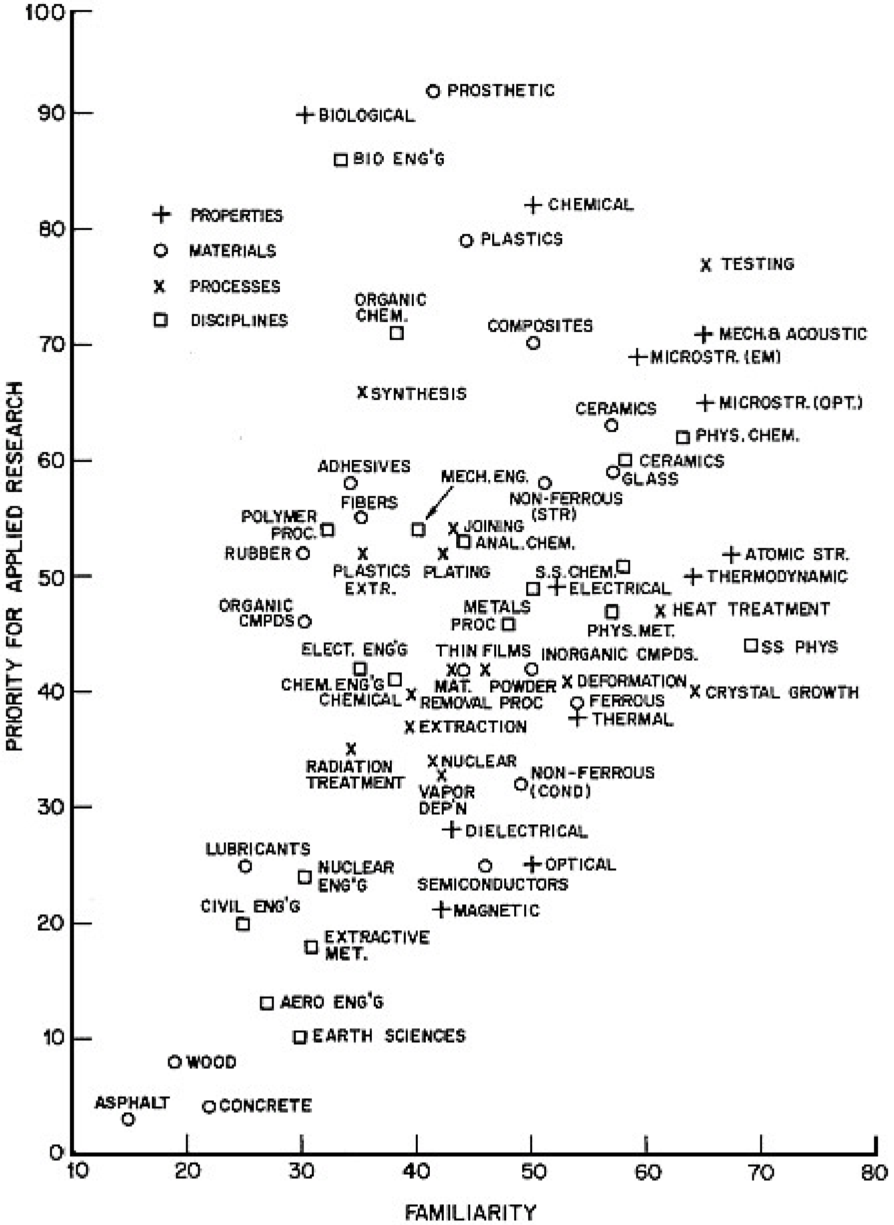

FIGURE 5.7 PRIORITY FOR APPLIED RESEARCH-AREA 60 HEALTH SERVICES

TABLE 5.16 Priority for Applied Research - Area 60 - Health Services

HEALTH SERVICES	Artificial Organs	Prosthetic Devices	
52	47	53	Atomic Structure
69	68	71	Microstructure (Electron Microscope Level)
65	64	69	Microstructure (Optical Microscope Level)
50	51	53	Thermodynamic
38	39	38	Thermal
71	75	79	Mechanical and Acoustic
25	23	16	Optical
49	54	38	Electrical
21	14	17	Magnetic
28	28	23	Dielectric
34	27	33	Nuclear
82	78	90	Chemical
90	95	92	Biological
63	53	71	Ceramics
59	55	62	Glasses and Amorphous Materials
25	19	16	Elemental and Compound Semiconductors
42	40	42	Inorganic, Nonmetallic Elements and Compounds
39	27	47	Ferrous Metals and Alloys
58	52	71	Nonferrous Structural Metals and Alloys
32	31	31	Nonferrous Conducting Metals and Alloys
79	67	82	Plastics
55	72	52	Fibers and Textiles
52	71	45	Rubbers
70	74	73	Composites
46	48	39	Organic and Organo-Metallic Compounds
42	53	34	Thin Films
58	70	59	Adhesives, Coatings, Finishes, Seals
25	30	19	Lubricants, Oils, Solvents, Cleansers
92	95	95	Prosthetic and Medical Materials
4	3	3	Plain and Reinforced Concrete
3	3	2	Asphaltic and Bituminous Materials
8	5	8	Wood and Paper

HEALTH SERVICES	Artificial Organs	Prosthetic Devices	
37	41	35	Extraction, Purification, Refining
66	82	63	Synthesis and Polymerization
40	38	42	Solidification and Crystal Growth
41	35	46	Metal Deformation and Processing
52	58	55	Plastics Extrusion and Molding
47	43	51	Heat Treatment
42	39	50	Material Removal
54	59	58	Joining
42	35	50	Powder Processing
33	35	32	Vapor and Electrodeposition, Epitaxy
35	38	25	Radiation Treatment
52	51	57	Plating and Coating
40	49	32	Chemical
77	78	78	Testing and Nondestructive Testing
10	3	7	Earth Sciences
53	53	52	Analytical Chemistry
62	68	61	Physical Chemistry
71	63	67	Organic and Polymer Chemistry
49	47	51	Inorganic Chemistry
51	56	50	Solid State Chemistry
44	43	39	Solid State Physics
60	56	65	Ceramics and Glass
34	67	51	Polymer Processing
18	13	19	Extractive Metallurgy
46	39	54	Metals and Inorganic Materials Processing
47	39	58	Physical Metallurgy
41	46	39	Chemical Engineering
54	57	57	Mechanical Engineering
42	41	32	Electronic Engineering
13	14	10	Aerospace Engineering
24	25	19	Nuclear Engineering
86	89	86	Bioengineering
20	17	16	Civil and Environmental Engineering

60 Health Services (21)

***Implants: compatibility; artificial bone, teeth, tissue, membranes; artificial organs; replacement for teeth; composites; surgical implants and prosthetics; better amalgram alloys

**Biophysics: understand enzymes; understand proteins; understand nucleids; stimulants and depressants; effect of drugs

*Diagnostic and preventive medicine using C13 cleansing materials; disposal of medical materials

*Reduce labor content of health services

61 Artificial Organs (65)

***Membranes; permeability dialysis
***Biocompatibility; surface reactions; rejection; blood compatibility; toxicity; surface effects
**Adhesion, prosthesis—tissue interface; attachment; adhesion between organs; bones, tissues
*Implants: organs, tooth, kidney, bones, transcutaneous materials, artificial heart, valves
*Mechanical properties: wear; residual stress; size and weight reduction
*Energy sources for artificial organs, moving parts, pacemakers, etc.

62 Medical Electronics (15)

***Sensors: high gain amplifiers for sense organs; chemical sensors; chemical monitors; permanent transcutaneous interface for patient monitoring; implanted sensors; encapsulants for implanted sensors; skin electrodes; microvoltronic implants
**Low cost diagnostic tools
**More sophisticated diagnostics; whole body surveys; catheters that can be left internally

63 Medical Equipment (including dental) (15)

***Implants: compatibility; methods to evaluate biocompatibility; characterization of properties for implants; simulated bone, teeth; tissue growth on bone implants; white dental filling; mixing machines for dental cements; fillings; corrosion; fatigue; wear
**Containers for blood; cryogenic preservation of organs; cryogenic preservation of semen
*Sensing devices; guided catheters

64 Prosthetic Devices (102)

Properties

***Prosthetic-tissue interface: stability; intergrowth; strength; rejection; bonding; chemistry

***Compatibility: rejection; imminological response; blood damage; clotting; compatibility with both tissue and bone

***Degradation: corrosion; durability; chemical stability; stress corrosion cracking; crevice corrosion; microbial corrosion

**Higher strength: pins; alloys for joints

*Controlled porosity

Materials

**Bone replacement: composites; ceramics; match strength and stiffness

**Better filling material for teeth

**Dental adhesives

*Steel alloys; high strength; corrosion resistant alloys

Processes

*Quality control

*Precision forming

*Processing fine wires; welding fine wires

Area 70 Housing and Other Construction

Under the area Housing and Other Construction, Mechanical and Acoustic, Chemical and Biological properties received the highest rating. Amongst the Materials, Plastics and Adhesives surprisingly received the highest rating for applied research as shown in Fig. 5.8. The three materials Wood, Asphalt and Concrete which lie at the bottom of all the other charts here assume a position of importance. Joining and Plastics Extrusion are the Processes that need most attention. Civil Engineering, Organic Chemistry and Mechanical Engineering are the most important Disciplines.

The overall comments on Housing and Construction emphasized improvements on construction and environmental protection. There were no comments under the sub-area of Construction Machinery. For Highways, Bridges, Airports, etc., improvements in road surfaces are needed. Suggestions such as polymer impregnated concrete or fiber concrete composites are possible solutions. Corrosion protection particularly for metal surfaces should receive high priority. Under Individual and Multiple Unit Dwellings, protection against the environment and improved resistance to burning received high priority, and the further development of prefabrication methods is also considered to be important. The development of low-cost polymers holds promise for the future. Under Industrial and Commercial Structures improvements in concrete would be valuable. Under Mobile Homes a variety of new materials and processes to reduce fabrication and component costs are needed. Under Plumbing, Heating, Electrical Etc., emphasis is given to environmental stability and safety.

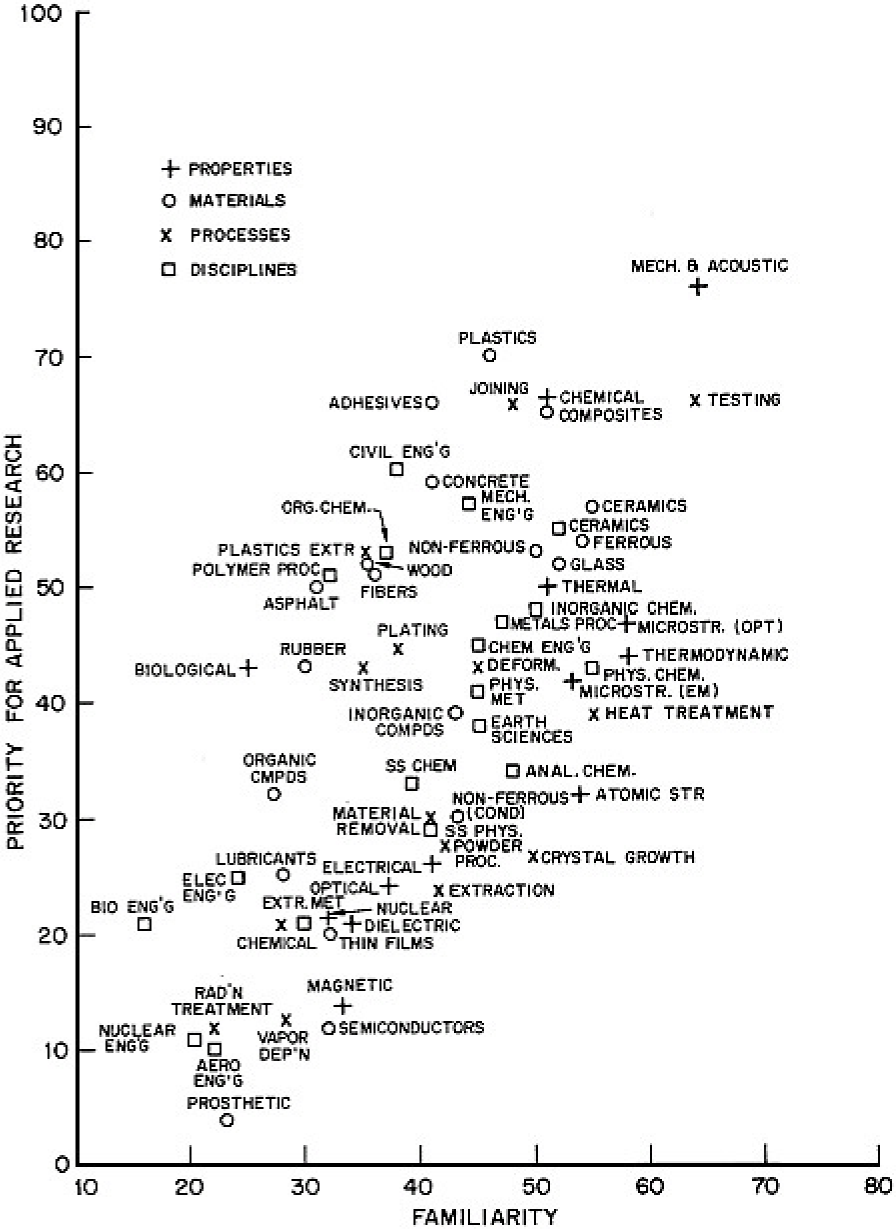

FIGURE 5.8 PRIORITY FOR APPLIED RESEARCH—AREA 70 HOUSING AND OTHER CONSTRUCTION

TABLE 5.17 Priority for Applied Research - Area 70 - Housing and Other Construction

HOUSING AND OTHER CONSTRUCTION	Individual and Multiple Unit Dwelling	Plumbing, Heating, Electrical, etc.	
32	27	28	Atomic Structure
42	43	29	Microstructure (Electron Microscope Level)
47	50	43	Microstructure (Optical Microscope Level)
44	42	46	Thermodynamic
50	52	60	Thermal
76	79	66	Mechanical and Acoustic
24	28	26	Optical
26	23	39	Electrical
14	13	16	Magnetic
21	21	20	Dielectric
21	18	13	Nuclear
66	69	62	Chemical
43	54	47	Biological
57	60	48	Ceramics
52	60	45	Glasses and Amorphous Materials
12	10	14	Elemental and Compound Semiconductors
39	36	26	Inorganic, Nonmetallic Elements and Compounds
54	48	67	Ferrous Metals and Alloys
53	50	57	Nonferrous Structural Metals and Alloys
30	32	31	Nonferrous Conducting Metals and Alloys
70	77	64	Plastics
51	63	20	Fibers and Textiles
43	50	25	Rubbers
65	70	42	Composites
32	34	20	Organic and Organo-Metallic Compounds
20	28	7	Thin Films
66	76	46	Adhesives, Coatings, Finishes, Seals
25	31	18	Lubricants, Oils, Solvents, Cleansers
4	4	0	Prosthetic and Medical Materials
59	63	23	Plain and Reinforced Concrete
50	50	23	Asphaltic and Bituminous Materials
52	64	25	Wood and Paper

HOUSING AND OTHER CONSTRUCTION	Individual and Multiple Unit Dwelling	Plumbing, Heating, Electrical, etc.	
24	23	31	Extraction, Purification, Refining
43	50	31	Synthesis and Polymerization
27	28	31	Solidification and Crystal Growth
43	42	43	Metal Deformation and Processing
53	64	45	Plastics Extrusion and Molding
39	39	41	Heat Treatment
30	29	21	Material Removal
66	71	51	Joining
28	35	19	Powder Processing
13	11	10	Vapor and Electrodeposition, Epitaxy
12	17	3	Radiation Treatment
45	45	35	Plating and Coating
21	25	16	Chemical
66	64	46	Testing and Nondestructive Testing
38	42	31	Earth Sciences
34	34	38	Analytical Chemistry
43	43	39	Physical Chemistry
53	60	39	Organic and Polymer Chemistry
47	47	42	Inorganic Chemistry
33	34	36	Solid State Chemistry
29	29	34	Solid State Physics
55	59	50	Ceramics and Glass
51	62	31	Polymer Processing
21	16	23	Extractive Metallurgy
47	49	56	Metals and Inorganic Materials Processing
41	34	46	Physical Metallurgy
45	50	46	Chemical Engineering
57	63	56	Mechanical Engineering
25	27	25	Electronic Engineering
10	10	5	Aerospace Engineering
11	9	6	Nuclear Engineering
21	23	14	Bioengineering
60	61	45	Civil and Environmental Engineering

70 Housing and Other Construction (24)

***Prefabrication: precast housing (e.g. reinforced plastic); improve pre-fab components; prefabricated housing; low cost modular construction; multi-layer panels; blended ceramics in liquid form

**Corrosion: atmospheric; underground; pitting

**Cement: reuse cement; breakup of bridge surfaces; reuseable concrete forms

*Fire-resistant materials

*Noise insulation; thermal insulation

*Wood substitutes

*Earthquake resistance

72 Highways, Bridges, Airports, etc, (22)

***Improved road surface: non-cement highway surfaces; pavement to withstand climate; impact of rolling loads; more permanent road surfaces; low-cost corrosion resistant concrete reinforcement; polymer impregnated concrete; fiber concrete; joint materials for bridges etc.

***Corrosion: need patching paints; protection and decoration; environmental damage; weather resistant components; corrosion of metal surfaces; deterioration

*Thermal stability
*Use natural materials
*Highway markings; signs

73 Individual and Multiple Unit Dwellings (59)

Properties

***Weatherability
***Flammability; fire safety

Materials

**Polymers
*Composites to replace steel and concrete
*Coatings
*Light, cheap brick

Processes

***Prefabrication: techniques; cost; new fabrication methods
**Low cost polymer fabrication
**Better control of materials; testing; evaluation
* Joining

74 Industrial and Commercial Structures (8)

**Concrete: fabricated steel shapes for reinforcement; cheap, fast setting light weight concrete
*Welding methods
*Use clay panelling
*Plastic structures
*Fireproof coatings
*Use aluminum

75 Mobile Homes (21)

***New materials: components with low assembly costs; techniques to adapt new materials; processing to reduce costs; ease of fabrication; sealants; synthetic foundations; metal; steel; ceramicoxide; low cost; better texture and warmth plastics
**Flammability: fire safety; fire resistant materials
**Testing: evaluative techniques; quality control
*Stiffness and strength
*Durability

76 Plumbing, Heating, Electrical, Etc. (26)

***Improved plumbing methods, materials, life durability; better coatings; improved enamel
*Improved heating systems; longer lasting; more efficient
*Fire safety; flame resistant materials and wiring
*Filters for ventilating systems

Area 80 Production Equipment

Mechanical and Acoustic Properties and Chemical Properties were given the highest ratings for Production Equipment as shown in Fig. 5.9. Non-Ferrous Structural Materials received the highest rating but Lubricants were also important although respondees were not as familiar with this area. Testing, Deformation and Joining are the most important processes in this area. Mechanical Engineering and Metal Processing are the important disciplines.

The overall comments on Production Equipment emphasize quality control.

In the sub-area of Farm and Construction Machinery, reliability was the principle concern, with corrosion, fatigue etc, being important areas for research. Under Industrial Drives, Motors, Controls, reliability was again the principle problem. Fatigue and corrosion were also important. Under Industrial Instrumentation, high temperature sensors were important. Again, reliability and corrosion were problems. Under Machine Tools, improved cutting materials with longer lives and higher reliability are needed. Under Process Equipment, the wear resistance of tools is important and so are other aspects of reliability. Improved methods for producing process equipment are needed.

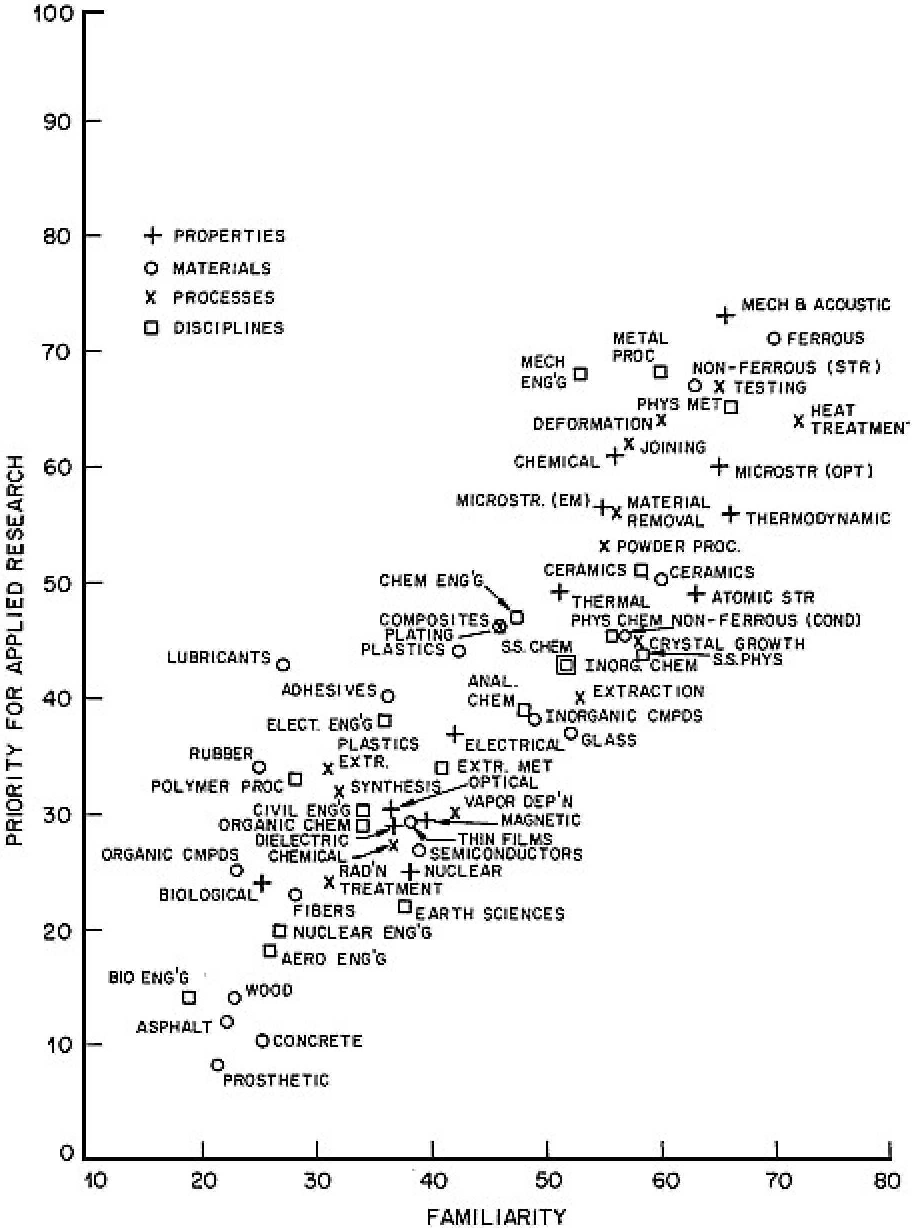

FIGURE 5.9 PRIORITY FOR APPLIED RESEARCH—AREA 80 PRODUCTION EQUIPMENT

TABLE 5.18 Priority for Applied Research - Area 80 - Production Equipment

PRODUCTION EQUIPMENT	Machine Tools	Process Equipment	
49	51	50	Atomic Structure
56	65	56	Microstructure (Electron Microscope Level)
60	66	60	Microstructure (Optical Microscope Level)
56	61	63	Thermodynamic
49	56	51	Thermal
73	73	76	Mechanical and Acoustic
30	21	27	Optical
37	19	36	Electrical
29	14	32	Magnetic
29	15	28	Dielectric
25	13	31	Nuclear
61	47	68	Chemical
24	9	29	Biological
50	53	55	Ceramics
37	26	41	Glasses and Amorphous Materials
27	13	21	Elemental and Compound Semiconductors
38	33	38	Inorganic, Nonmetallic Elements and Compounds
71	76	75	Ferrous Metals and Alloys
67	60	75	Nonferrous Structural Metals and Alloys
46	34	48	Nonferrous Conducting Metals and Alloys
44	21	48	Plastics
23	9	28	Fibers and Textiles
34	19	39	Rubbers
46	38	48	Composites
25	23	23	Organic and Organo-Metallic Compounds
29	15	28	Thin Films
40	19	50	Adhesives, Coatings, Finishes, Seals
43	40	46	Lubricants, Oils, Solvents, Cleansers
8	3	8	Prosthetic and Medical Materials
11	3	17	Plain and Reinforced Concrete
12	3	15	Asphaltic and Bituminous Materials
14	3	16	Wood and Paper

PRODUCTION EQUIPMENT	Machine Tools	Process Equipment	
40	35	52	Extraction, Purification, Refining
32	26	37	Synthesis and Polymerization
45	38	52	Solidification and Crystal Growth
64	64	67	Metal Deformation and Processing
34	26	31	Plastics Extrusion and Molding
64	75	67	Heat Treatment
56	75	56	Material Removal
62	63	64	Joining
53	60	56	Powder Processing
30	30	28	Vapor and Electrodeposition, Epitaxy
24	19	17	Radiation Treatment
46	50	47	Plating and Coating
28	28	23	Chemical
67	67	64	Testing and Nondestructive Testing
22	18	25	Earth Sciences
39	25	42	Analytical Chemistry
46	42	52	Physical Chemistry
29	15	32	Organic and Polymer Chemistry
43	39	45	Inorganic Chemistry
43	46	42	Solid State Chemistry
44	46	38	Solid State Physics
51	56	56	Ceramics and Glass
33	25	38	Polymer Processing
34	28	43	Extractive Metallurgy
66	67	76	Metals and Inorganic Materials Processing
65	68	64	Physical Metallurgy
47	31	59	Chemical Engineering
68	67	73	Mechanical Engineering
38	27	37	Electronic Engineering
18	22	14	Aerospace Engineering
20	18	19	Nuclear Engineering
14	10	16	Bioengineering
30	18	32	Civil and Environmental Engineering

80 Production Equipment (10)

**Quality control
**Weldability; of steels

81 Farm and Construction Machinery (14)

***Wear: abrasion resistance; wear and corrosion; tribology-lubricants
**Corrosion
*Fatigue
*Brittle fracture
*Strength
*Welding
*Assembly methods

82 Industrial Drives, Motors, Controls (14)

**Wear; friction; wear resistance; lubricants
*Fatigue; fatigue failure
*Corrosion resistant coatings; paints
*New abrasives
*Compact motors
*Noise suppression
*Energy consumption

83 Industrial Instrumentation (7)

**High temperature sensors; high temperature thermocouple alloys; optical measuring methods; high temperature abrasion; corrosion
*Corrosion service
*Reliable electrical contacts

84 Machine Tools (22)

***Tool materials: longer lasting; higher speed; higher temperature and pressure; improve wear and fatigue properties
*Grinding: improve use of alumina, improve uniformity of grinding wheels
*Welding: develop electron beam and laser welding

85 Process Equipment (97)

Properties

***Wear resistance: harder dies, better cutting tools, saws, grinding materials, valves
**Better high temperature strength
**Corrosion resistance, rusting, stress corrosion cracking
*Surface integrity
*Alloys and seals for chemical processing in radiation environment

Materials

*Cold-forming materials
*Better gaskets
*Vacuum seals
*Composite materials

Processes

***More automation, faster, more efficient, cheaper, more reliable
**New casting methods; new foundary process; improved reduction, refining, solidification
*Warping and cracking during heat treatment
*Wool processing equipment

Area 90 Transportation Equipment

The most important properties for Transportation Equipment are Mechanical and Acoustic and Chemical Properties, as shown in Fig. 5.10. The materials which received the highest rating were Composites, Adhesives and Lubricants. The Processes of Joining, Material Removal, Plating and Plastic Extrusion were important. The most relevant Disciplines were Metal Processing, Polymer Processing and Electrical Engineering.

The overall comments for this area again stressed reliability, particularly corrosion resistance. The problems of pollution from engines and fuel cells were also important. The mechanical properties such as strength-to-weight ratio for structural components of all kinds, and especially high temperature alloys for turbines were important materials limitations in this area. Under the subheading Aircraft, mechanical properties such as improved strength-to-weight ratio and improved high temperature materials again rated high. The reliability, corrosion protection and improvement of fatigue characteristics were important. Further developments in joining methods are needed. In the Automotive sub-area, mechanical properties were important, with improved strength-to-weight materials required for automobile bodies and engines, especially high temperature materials for gas turbines. Improved impact resistance, corrosion and fatigue were again important problems. The control of pollution of the environment was important. New adhesives were needed. Under Guided Ground Transportation, emphasis was placed on the need for further research to develop superconductor systems. Again materials with improved mechanical properties and improved wear properties were needed. Under Water Transportation Equipment the chief concern was environmental protection from corrosion.

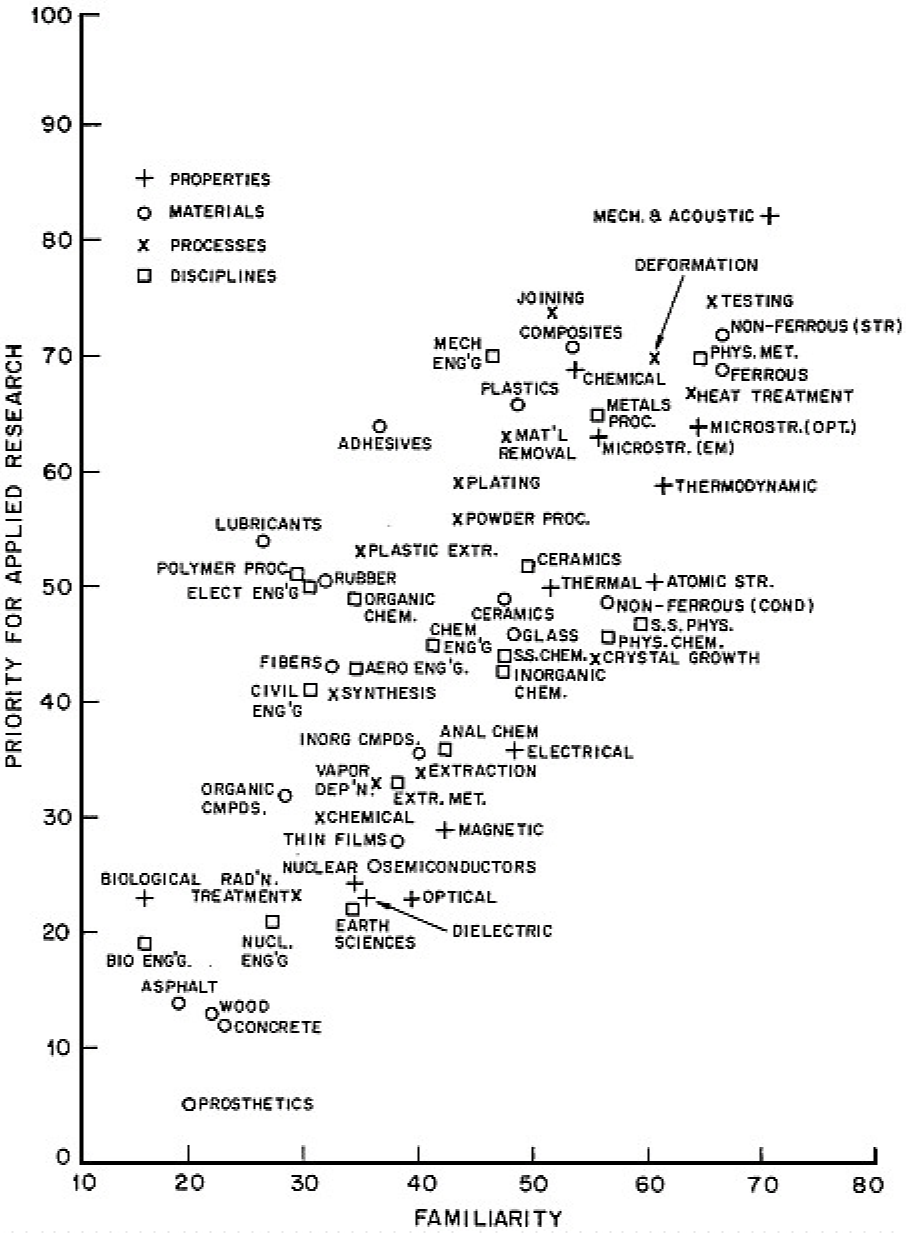

FIGURE 5.10 PRIORITY FOR APPLIED RESEARCH—AREA 90 TRANSPORTATION EQUIPMENT

TABLE 5.19 Priority for Applied Research - Area 90 - Transportation Equipment

TRANSPORTATION EQUIPMENT	Aircraft	Automotive	Guided Ground Transportation	
50	46	52	41	Atomic Structure
63	74	63	51	Microstructure (Electron Microscope Level)
64	70	67	49	Microstructure (Optical Microscope Level)
59	60	64	54	Thermodynamic
50	51	50	50	Thermal
85	91	84	79	Mechanical and Acoustic
23	19	25	25	Optical
36	23	37	64	Electrical
29	14	26	61	Magnetic
23	14	25	35	Dielectric
24	19	25	20	Nuclear
69	65	76	51	Chemical
23	10	32	19	Biological
49	49	53	40	Ceramics
46	39	51	39	Glasses and Amorphous Materials
26	23	25	28	Elemental and Compound Semiconductors
36	35	38	30	Inorganic, Non-Metallic Elements and Compounds
69	67	74	63	Ferrous Metals and Alloys
72	87	67	67	Non-Ferrous Structural Metals and Alloys
49	35	48	66	Non-Ferrous Conducting Metals and Alloys
66	65	71	53	Plastics
43	39	53	25	Fibers and Textiles
50	45	63	34	Rubbers
71	84	70	56	Composites
32	36	35	20	Organic and Organo-Metallic Compounds
28	31	24	28	Thin Films
64	68	67	46	Adhesives, Coatings, Finishes, Seals
54	53	57	42	Lubricants, Oils, Solvents, Cleansers
5	2	5	2	Prosthetic and Medical Materials
12	1	4	31	Plain and Reinforced Concrete
14	3	14	21	Asphaltic and Bituminous Materials
13	8	14	9	Wood and Paper

TRANSPORTATION EQUIPMENT	Aircraft	Automotive	Guided Ground Transportation	
34	29	34	32	Extraction, Purification, Refining
41	41	41	40	Synthesis and Polymerization
44	52	47	38	Solidification and Crystal Growth
70	76	71	64	Metal Deformation and Processing
53	49	61	39	Plastics Extrusion and Molding
67	68	74	56	Heat Treatment
63	75	66	36	Material Removal
74	84	75	56	Joining
56	56	66	40	Powder Processing
33	33	33	32	Vapor and Electrodeposition, Epitaxy
23	19	26	23	Radiation Treatment
59	62	65	42	Plating and Coating
30	29	33	25	Chemical
75	87	72	52	Testing and Non-Destructive Testing
22	14	18	29	Earth Sciences
36	31	42	25	Analytical Chemistry
46	40	52	39	Physical Chemistry
49	50	54	33	Organic and Polymer Chemistry
43	39	46	39	Inorganic Chemistry
44	39	46	48	Solid State Chemistry
47	42	50	59	Solid State Physics
52	49	60	38	Ceramics and Glass
51	53	58	33	Polymer Processing
33	30	33	30	Extractive Metallurgy
65	73	69	52	Metals and Inorganic Materials Processing
70	81	67	65	Physical Metallurgy
45	41	52	36	Chemical Engineering
70	76	68	64	Mechanical Engineering
50	53	43	62	Electronic Engineering
43	76	22	32	Aerospace Engineering
21	19	13	23	Nuclear Engineering
19	12	21	18	Bioengineering
41	27	41	52	Civil and Environmental Engineering

90 Transportation Equipment (45)

***Corrosion resistance; stress corrosion; corrosion fatigue; stress corrosion cracking; high temperature oxidation; refractory coatings

***Pollution: catalytic converters; low emission engines; non-polluting effluents for water vehicle; automobile pollution control; pollution; non-polluting fuel cells

**Strength/Weight: strength; density; lighter auto bodies; stronger, lighter materials

**Strength; strong materials for ship propellers; for high speed ground transportation

**High temperature materials for gas turbines; high temperature alloys; high temperature; corrosion resistant materials

*Friction

*Composite materials; joining composite materials

*Safety equipment for autos

*NDT for tires

*Magnetic levitation; magnetic materials

*Guidance systems

91 Aircraft (54)

***Improved strength/weight; lower cost, new alloys; composites
**High temperature materials for gas turbines; superalloys for engines
**Corrosion; stress corrosion; oxidation; corrosion fatigue
**Joining; adhesives; fasteners; bonding systems; sealants
**Fatigue; crack propagation; high temperature cycling
*Mechanical properties: fracture toughness, impact resistance, creep rupture
*New materials: Ti alloys, Be alloys, superalloys
*Testing, non-destructive evaluation

92 Automotive (59)

Properties

***Higher strength/weight materials for auto bodies, engines
***Impact resistance: energy absorbing materials
***Corrosion resistance for body, for exhaust systems
***High temperature materials for gas turbines
**Wear of tires, reliable tires

Materials

***Lighter, stronger materials for bodies and engines, e.g. composites, aluminum, plastics
***Catalysts for emission control: housing for burners, coatings for mufflers
***Adhesives for bodies, frames, repairs
**Safety glass
*Seals for gas turbines, for Wankel engines
*Replacement for gasoline, different compositions for gasoline

Processes

**Test for emission control, laser detection system
**Fatigue sensors
*Fabrication processes for tires, castable tires

93 Guided Ground Transportation (37)

***Superconductors: large scale cryogenic systems; superconducting magnets; superconducting levitation; superconducting magnets for levitation; for magnets for motors; for propulsion
**Higher strength to weight; lightweight structural materials; design of lightweight structures
*Cheap high-conductivity guides
*Sensors for traffic control
*Brake materials for trains; for high speeds
*Electrical contacts
*Improved castings
*High efficiency batteries
*Better bearings
*Tough rail-wheel systems
*Low-noise rolling stock
*Ventilation
*Tunneling methods

94 Water (6)

**Salt water environment; environmental protection
*Lightweight structure
*Drag reduction
*Conversion of salt water to potable water

APPENDIX 5A

NATIONAL ACADEMY OF SCIENCES
NATIONAL RESEARCH COUNCIL

COMMITTEE ON THE SURVEY OF MATERIALS SCIENCE AND ENGINEERING
2101 CONSTITUTION AVENUE. N.W. WASHINGTON. D.C. 20418

Priorities in Materials Science and Engineering

Dear Colleague:

This letter and its attachments constitute an attempt by the National Academy of Sciences (NAS) Committee on the Survey of Materials Science and Engineering (COSMAT) to investigate the matter of priorities among the various activities that make up the field of materials science and engineering. We wish to do this from two points-of-view: (1) the potential impact of materials science and engineering on a variety of broad applications having important economic or social consequences, and (2) the intrinsic scientific or technical opportunities for significant advances within designated activities of materials science and engineering.

To accomplish this task, we are writing to a selected group of persons knowledgeable in various aspects of the field in order to obtain a good sample of expert judgment bearing on the problem of priorities. In the course of events, such priorities do merge in one way or another, but now we are trying to secure a more adequate technical input for the process. The results will be extremely useful to COSMAT not only in identifying areas of opportunity for materials science and engineering and its associated disciplines, but also in discerning instances of imbalance in the field. Moreover, these findings will provide a valuable source of information to many institutions in industry, government and universities for setting their own priorities on programs and funding according to their respective objectives and missions.

The overall COSMAT study is being conducted under the aegis of the NAS Committee on Science and Public Policy, and follows the previous surveys conducted by the Academy on mathematics, astronomy, physics, chemistry and life sciences. It is the first survey that addresses a field encompassing both science and engineering. COSMAT is seeking to (a) define the nature and scope of materials science and engineering, (b) establish how basic knowledge is transmitted into useful applications in this multidisciplinary field, (c) analyze the role of materials in our culture and technology, (d) determine the major opportunities and roadblocks in materials science and engineering, and (e) assess the ways in which materials science and engineering can contribute more effectively to society. It is anticipated that the main Survey Report will be published by the end of this year.

We recognize that filling out the enclosed form will require about an hour of your time, but we feel justified in asking you for this effort because of the potential importance of the survey. Indeed, once you have "entered" the questionnaire, you may find yourself being stimulated by the exercise. We urge your thoughtful cooperation, and shall be grateful for it.

Kindly return the completed form to the COSMAT office within two weeks if at all possible. For your convenience, a return label is attached. If you wish to receive a copy of the data analysis, please so indicate on the last page of the questionnaire.

Sincerely yours,

Morris Cohen
Morris Cohen
Chairman, COSMAT

W. O. Baker
William O. Baker
Vice-Chairman, COSMAT

Attachments
20 June 1972

NATIONAL ACADEMY OF SCIENCES
NATIONAL RESEARCH COUNCIL
COMMITTEE ON THE SURVEY OF MATERIALS SCIENCE AND ENGINEERING
2101 CONSTITUTION AVENUE, N.W.
WASHINGTON. D.C. 20418

INSTRUCTIONS FOR COMPLETING THE QUESTIONNAIRE ON PRIORITIES IN THE FIELD OF MATERIALS SCIENCE AND ENGINEERING

JUNE 1972

OMB No. 099S72003
Expires 8/31/72

GENERAL INSTRUCTIONS

The working definition of Materials Science and Engineering that has been tentatively adopted by the Survey Committee is:

> Materials Science and Engineering is concerned with the generation and application of knowledge relating the composition, structure and processing of materials to their properties and beneficial use.

As will be realized, this fairly broad definition embraces several scientific and engineering disciplines, and segments of disciplines. It embraces basic research, applied research and engineering, and it embraces a variety of classes of materials, particularly ceramics, electronic materials, glass, metals and plastics.* However, the Committee has chosen not to include certain classes such as food, drugs, pesticides and fuels used in essentially their natural state. The focus is on materials which are useful in machines, devices, structures or products.

On the following pages of this Priority Survey you will find the headings:

I - The Overall Importance of Materials Science and Engineering to Each Area of Impact
II - Statements of Materials Problems in Selected Sub-Areas of Impact
III - A. Priority Information Relating to Properties of Materials
  B. Priority Information Relating to Classes of Materials
  C. Priority Information Relating to Processes for Materials
  D. Priority Information Relating to Disciplines and Sub-Disciplines in the Field of Materials Science and Engineering
IV - Personal Information

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*A more complete list of materials appears in Table IIIB.

SPECIFIC INSTRUCTIONS

Specific instructions are given on each page. Please read and follow these carefully. In several parts of this questionnaire you are asked to respond using a rating scale of from 1 (for Very High Importance or Priority) to 5 (for Very Low Importance or Priority). The following definitions might help you in using this rating scale:

1— Very High
Advances in the field or specialty of Materials Science and Engineering are essential for substantial further progress in the Area or Sub-Area being considered; achievements of the future goals or objectives in the area probably cannot be attained at reasonable cost unless advances are made in Materials Science and Engineering.

2— High
Somewhere between Very High and Moderate.

3— Moderate
Advances in the field or specialty of Materials Science and Engineering will contribute importantly to further progress in the Area or Sub-Area being considered; achievement of the future goals or objectives in the area will be helped considerably by advances in Materials Science and Engineering although some progress can be achieved without notable contributions from Materials Science and Engineering.

4— Low
Somewhere between Moderate and Very Low.

5— Very Low
Advances in the field or specialty of Materials Science and Engineering, although helpful, are not of great importance to further progress in the Area or Sub-Area being considered; achievement of the future goals or objectives in the area is possible with little or no contribution from Materials Science and Engineering.

LIST OF AREAS AND SUB-AREAS OF IMPACT

Code Number	
10	COMMUNICATIONS, COMPUTERS AND CONTROL
11	Commercial Radio and TV Equipment
12	Computers
13	Electronic Components
14	Equipment for Guidance and Control of Transportation
15	Teaching Equipment
16	Telephone and Data Networks and Equipment
20	CONSUMER GOODS
21	Apparel and Textiles
22	Furniture
23	Household Appliances—Electronic (TV, radio, hi-fi, etc.)
24	Household Appliances—Non-Electronic (refrigerators, ranges, air conditioners, vacuum cleaners, etc.)
25	Leisure and Sports Equipment
26	Packaging and Containers
27	Printing and Photography
30	DEFENSE AND SPACE
31	Military Aircraft
32	Missiles
33	Naval Vessels
34	Ordnance and Weapons
35	Radar and Military Communications
36	Spacecraft
37	Undersea Equipment
40	ENERGY
41	Batteries and Fuel Cells
42	Direct Conversion
43	Electric Transmission and Distribution
44	Fuel Transmission and Distribution
45	Nuclear Reactors
46	Thermonuclear Fusion
47	Turbines and Generators
50	ENVIRONMENTAL QUALITY
51	Mining and Raw Material Extraction
52	Pollution
53	Recycling and Solid Wsste Disposal
54	Reliability, Safety, Maintainability
55	Substitution Opportunities
56	Working Conditions
60	HEALTH SERVICES
61	Artificial Organs
62	Medical Electronics
63	Medical Equipment (including dental)
64	Prosthetic Devices (including dental)
70	HOUSING AND OTHER CONSTRUCTION
71	Construction Machinery
72	Highways, Bridges, Airports, etc.
73	Individual and Multiple Unit Dwellings
74	Industrial and Commercial Structures
75	Mobile Homes
76	Plumbing, Heating, Electrical, etc.
80	PRODUCTION EQUIPMENT
81	Farm and Construction Machinery
82	Industrial Drives, Motors, and Control
83	Industrial Instrumentation
84	Machine Tools
85	Process Equipment
90	TRANSPORTATION EQUIPMENT
91	Aircraft
92	Automotive
93	Guided Ground Transportation (rail, non-rail)
94	Water

NATIONAL ACADEMY OF SCIENCES
NATIONAL RESEARCH COUNCIL
COMMITTEE ON THE SURVEY OF MATERIALS SCIENCE AND ENGINEERING
2101 CONSTITUTION AVENUE, N.W.
WASHINGTON, D. C. 20418

QUESTIONNAIRE ON PRIORITIES IN THE FIELD OF MATERIALS SCIENCE AND ENGINEERING

JUNE 1972

I. THE OVERALL IMPORTANCE OF MATERIALS SCIENCE AND ENGINEERING TO EACH AREA OF IMPACT

On this page please circle the appropriate number against each Area of Impact in answer to the question, "What is the Overall Importance of Materials Science and Engineering?"

Area of Impact		Very High	High	Moderate	Low	Very Low
10	COMMUNICATIONS, COMPUTERS AND CONTROL	1	2	3	4	5
20	CONSUMER GOODS	1	2	3	4	5
30	DEFENSE AND SPACE	1	2	3	4	5
40	ENERGY	1	2	3	4	5
50	ENVIRONMENTAL QUALITY	1	2	3	4	5
60	HEALTH SERVICES	1	2	3	4	5
70	HOUSING AND OTHER CONSTRUCTION	1	2	3	4	5
80	PRODUCTION EQUIPMENT	1	2	3	4	5
90	TRANSPORTATION EQUIPMENT	1	2	3	4	5

II. STATEMENTS OF MATERIALS PROBLEMS IN SELECTED SUB-AREAS OF IMPACT

From the List of Areas and Sub-Areas select up to 5 Sub-Areas in which you feel you are knowledgeable or to which your experience relates. Refer to these Sub-Areas by entering the appropriate Code Numbers below in the spaces marked A to E. For each Sub-Area you select please give brief statements of 3 materials problems that you judge are of critical importance for progress in the Sub-Area to occur. (Note: The letters A to E are not meant to imply any relative rankings among the Sub-Areas.)

MATERIALS PROBLEMS

Sub-Area Code Number A___	1
2	
3	
Sub-Area Code Number B___	1
2	
3	
Sub-Area Code Number C___	1
2	
3	
Sub-Area Code Number D___	1
2	
3	
Sub-Area Code Number E___	1
2	
3	

III. A. PRIORITY INFORMATION RELATING TO PROPERTIES OF MATERIALS

Using the given rating scale, enter an appropriate rating in every box of the table in answer to the questions posed at the top of the columns at the left and at the right.

APPLIED RESEARCH AND ENGINEERING

What level of priority should be given to Applied Research and Engineering concerning the given specialty in order for progress to occur in each Sub-Area you selected? Complete the whole column for each Sub-Area you select.

SUB-AREAS OF IMPACT
(Write at head of each column a Code Number you used on Sheet II.)

Rating Scale:
1 - Very High
2 - High
3 - Moderate
4 - Low
5 - Very Low

BASIC RESEARCH

For each specialty enter in the column at the left what level of priority should be given to Basic Research not yet identified with any particular Area of Impact. For those specialties you rate most highly please give statement of research you have in mind.

A	B	C	D	E	Your Familiarity with Specialty?	SPECIALTY	Level of Priority	STATE NATURE OF RESEARCH
						Atomic Structure (Crystallography and Defects)		
						Microstructure (Electron Microscope Level)		
						Microstructure (Optical Microscope Level)		
						Thermodynamic (Phase Equilibria, Change of State, etc.)		
						Thermal (Thermal Conductivity, Phonons, Diffusion, etc.		
						Mechanical and Acoustic (Strength, Creep, Fatigue, Damping, etc.)		
						Optical (Emission, Absorption, Luminescence, Excitation, Transmission, etc.)		
						Electrical (Conduction, Electron Transport, Ionic Conductivity, Thermoelectric, Injection, Carrier Phenomena, etc.		
						Magnetic (Ferromagnetic, Resonance, Paramagnetic, etc.)		
						Dielectric (Ferroelectric, Breakdown, Loss, Piezoelectric, etc.)		
						Nuclear (Radiation Damage, Absorption, Surface States, Catalysis, etc.)		
						Chemical and Electrochemical (Corrosion, Battery Phenomena, Oxidation, Flammability, etc.)		
						Biological (Toxicity, Biodegradable, etc.)		

III. B. PRIORITY INFORMATION RELATING TO CLASSES OF MATERIALS

Using the given rating scale enter an appropriate rating in every box of the table in answer to the questions posed at the top of the columns at the left and at the right.

APPLIED RESEARCH AND ENGINEERING

What level of priority should be given to Applied Research and Engineering concerning the given specialty in order for progress to occur in each Sub-Area you selected? Complete the whole column for each Sub-Area you select.

SUB-AREAS OF IMPACT
(Write at head of each column a Code Number you used on Sheet II.)

Rating
Scale: 1 - Very High
2 - High
3 - Moderate
4 - Low
5 - Very Low

BASIC RESEARCH

For each specialty enter in the column at the left what level of priority should be given to Basic Research not yet identified with any particular Area of Impact. For those specialties you rate most highly please give statement of research you have in mind.

A	B	C	D	E	Your Familiarity With Specialty	SPECIALTY	Level of Priority	STATE NATURE OF RESEARCH
						Ceramics		
						Glasses and Amorphous Materials		
						Elemental and Compound Semiconductors		
						Inorganic, Non-Metallic Elements and Compounds (not included elsewhere)		
						Ferrous Metals and Alloys		
						Non-Ferrous Structural Metals and Alloys		
						Non-Ferrous Conducting Metals and Alloys		
						Plastics		
						Fibers and Textiles		
						Rubbers		
						Composites		
						Organic and Organo-Metallic Compounds		
						Thin Films		
						Adhesives, Coatings, Finishes, Seals		
						Lubricants, Oils, Solvents, Cleansers		
						Prosthetic and Medical Materials		
						Plain and Reinforced Concrete		
						Asphaltic and Bituminous Materials		
						Wood and Paper		

(5)

III. C. PRIORITY INFORMATION RELATING TO PROCESSES FOR MATERIALS

Using the given rating scale enter an appropriate rating in every box of the table in answer to the questions posed at the top of the columns at the left and at the right.

APPLIED RESEARCH AND ENGINEERING

What level of priority should be given to Applied Research and Engineering concerning the given specialty in order for progress to occur in each Sub-Area you selected? Complete the whole column for each Sub-Area you select.

SUB-AREAS OF IMPACT

(Write at head of each column a Code Number you used on Sheet II.)

Rating Scale:
1 - Very High
2 - High
3 - Moderate
4 - Low
5 - Very Low

BASIC RESEARCH

For each specialty enter in the column at the left what level of priority should be given to Basic Research not yet identified with any particular Area of Impact. For those specialties you rate most highly please give statement of research you have in mind.

A	B	C	D	E	Your Familiarity With Specialty	SPECIALTY	Level of Priority	STATE NATURE OF RESEARCH
						Extraction, Purification, Refining		
						Synthesis and Polymerization		
						Solidification and Crystal Growth		
						Metal Deformation and Processing		
						Plastics Extrusion and Molding		
						Heat Treatment		
						Material Removal (Machining, Electrochemical, Chemical, Grinding, etc.)		
						Joining (Welding, Soldering, Brazing, Adhesive Bonding, etc.)		
						Powder Processing		
						Vapor and Electrodeposition, Epitaxy		
						Radiation Treatment (Ion Implantation, Electron Beam, UV, etc.)		
						Plating and Coating		
						Chemical (Doping, Photoprocessing, Etching, etc.)		
						Testing and Non-Destructive Testing		

(6)

III. D. PRIORITY INFORMATION RELATING TO DISCIPLINES AND SUB-DISCIPLINES IN THE FIELD OF MATERIALS SCIENCE AND ENGINEERING

Using the scale at the left, enter an appropriate rating in every box of the table in answer to the questions posed at the top.

Scale:
1 - Very High
2 - High
3 - Moderate
4 - Low
5 - Very Low

What level of priority should be given to activity concerning the given Discipline or Sub-Discipline in order for progress to occur in each Sub-Area you selected? Complete the whole column for each Sub-Area you select.

SUB-AREAS
(Write at head of each column a Code Number you used on Sheet II.)

DISCIPLINE OR SUB-DISCIPLINE	Your Familiarity With Specialty	A	B	C	D	E
Earth Sciences						
Analytical Chemistry						
Physical Chemistry						
Organic and Polymer Chemistry						
Inorganic Chemistry						
Solid State Chemistry						
Solid State Physics						
Ceramics and Glass						
Polymer Processing						
Extractive Metallurgy						
Metals and Inorganic Materials Processing						
Physical Metallurgy						
Chemical Engineering						
Mechanical Engineering						
Electronic Engineering						
Aerospace Engineering						
Nuclear Engineering						
Bioengineering						
Civil and Environmental Engineering						
Other (Specify)						

IV. PERSONAL INFORMATION

After completing the previous sheets would you kindly give us the following information:

1. Your Highest Degree:
   None____, Bachelor____, Master____, Doctor____.
2. Discipline of Highest Degree____________________.
3. Your Age Bracket:
   Under 30____, 30 to 30____, 40 to 49____, 50 and over____.
4. Employment:

a) Type of Institution:
   Academic____, Government____, Industrial____, Non-Profit____, Other (specify) ____.
b) Types of Activity:
   Teaching____, Research____, Development or Engineering____, Technical Management____, General Management____, Other (specify)____.
   If you checked a Management Category, the number of personnel reporting to you is:
   less than 10____, 10 to 100____, over 100____.

5. OPTIONAL:
   Name:
   Title:
   Employment Address:

DATA ANALYSIS: Do you wish to receive a copy of the data analysis?

Yes____ No____

CHAPTER 6

OPPORTUNITIES IN MATERIALS RESEARCH*

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*This chapter was prepared by a Task Force that included E.A.Chandross, G.Y.Chin, A.G.Chynoweth (chairman), T.D.Dudderar, P.A.Fleury, R.Frankenthal, F.T.Geyling, K.A.Jackson, P.L.Key, R.A.Laudise, L.D.Loan, S.Mahajan, D.K.Rider, M.D.Rigterink, T.D.Schlabach, W.P.Slichter, J.H.Wernick, and F.H.Winslow. As part of its work, this Task Force analyzed and summarized the large number of letters that were received in reply to invitations sent out by COSMAT to scientists and engineers in the materials field seeking their opinions about materials research opportunities. Most of these scientists and engineers were reached through the professional societies. Others were reached through appropriate Gordon Research Conferences. A few were identified individually.

The Professional Societies whose help was solicited in this part of the COSMAT Study included:

American Ceramic Society
American Chemical Society
American Concrete Institute
American Foundrymen's Society
American Institute of Aeronautics and Astronautics
American Institute of Chemical Engineers
American Institute of Mining, Metallurgical, and Petroleum Engineers
American Iron and Steel Institute
American Nuclear Society
American Physical Society
American Society of Civil Engineers
American Society of Mechanical Engineers
American Society for Metals
American Society for Nondestructive Testing
American Society for Quality Control
American Society for Testing and Materials
American Welding Society
Association of Iron and Steel Engineers
Electrochemical Society
Electron Microscopy Society of America
Federation of Societies for Paint Technology
Forest Products Research Society
Institute of Electrical and Electronic Engineers
Instrument Society of America
National Association of Corrosion Engineers
National Association of Power Engineers
Optical Society of America
Society of Aerospace Material and Process Engineers

Society of Automotive Engineers
Society for Experimental Stress Analysis
Society of Manufacturing Engineers
Society of Plastics Engineers

The Gordon Research Conferences (1972) through which solicitations were made included:

Analytical Chemistry
Atomic and Molecular Interactions
Chemistry and Metallurgy of Semiconductors
Chemistry of Molten Salts
Chemistry and Physics of Cellular Materials
Chemistry and Physics of Coatings and Films
Chemistry and Physics of Inorganic Phosphors
Chemistry and Physics of Liquids
Chemistry and Physics of Paper
Chemistry and Physics of Solids
Corrosion
Crystal Growth
Elastomers
Environmental Sciences: Air
Geochemistry
Inorganic Chemistry
Ion Exchange
Laser Interactions with Matter
Natural Products
Organic Photochemistry
Polymers
Science of Adhesion
Separation and Purification
Technology of Biomaterials
Thin Films

CHAPTER 6

OPPORTUNITIES IN MATERIALS RESEARCH

INTRODUCTION

The broad aim in materials research is to develop fundamental and general understanding of the properties and performance of materials and how these relate to their composition, structure and processing. Increasingly, this knowledge is expressed in terms of the fundamental, individual and collective properties of atoms and electrons. Increasingly, phenomenological or analytical models of materials at this basic atom-electron level are becoming a common language that spans many scientific disciplines, science and engineering, and catalyses effective communication and knowledge-transfer back and forth among the materials community. Whether the initial stimulus for seeking this knowledge is largely curiosity or the prospect of an application, the approach and objective is much the same—to acquire fundamental knowledge which can, in turn, be used in a rigorous, direct, predictive way to advance with confidence the frontiers of materials capability. The alternative to understanding at the microstructural and atom-electron level is to rely primarily on empirical methods which, though often expedient and dramatically successful, provide few guides to whether further improvement is possible.

Despite the many impressive achievements of materials research there is the awareness that only the surface of scientific capability has been scratched. The majority of advances have historically been made via the empirical approach. Most new materials or properties are arrived at or discovered by cut-and-try methods—new chemical or alloy compositions are prepared and characterized and their various properties are determined. There are usually underlying rationales or phenomenological models to this empirical approach but it is rare indeed for a new material or property to be predicted from basic principles. The principal exception to this situation is in the area of single crystal materials, particularly those used in solid state electronics. On the other hand, techniques and concepts of physical science are often essential for characterizing and reproducing the properties of even empirically-invented materials. With electronic materials, due to the combined talents of chemists, metallurgists, physicists and electrical engineers a degree of understanding has been achieved, at least for the simpler crystals, so that material compositions having the desired physical properties can often be prescribed beforehand.

An important key to this progress in electronic materials is the single crystal state of the material—a state which lends itself to theoretical analysis. Only relatively recently has the attention of basic research scientists been turning towards other, more complex forms of matter, such as the glassy, polycrystalline and polymeric states characteristic of the majority of practical materials, particularly those used in structural applications. It is reasonable to hope that the levels of sophistication that materials scientists and engineers have achieved with single crystal materials will, in due course, be paralleled by achievements with these more complex states of matter.

In the following paragraphs some illustrative examples will be given of opportunities for research in materials. Whether these opportunities are curiosity- or applications-stimulated they have in common a primary aim of arriving at fundamental knowledge at the atom-electron level. Some of this knowledge, when obtained, may have immediate applicability, some may be many years ahead of its application, and some may never find practical use although it may still contribute to general conceptualisation of understanding about materials. While the need and urgency for acquiring knowledge will vary in different parts of materials science, leading to the setting of priorities, it is impossible to conclude that even the most esoteric and apparently irrelevant research topics in materials science, judged by today's standards, will not prove of value at some time in the future.

This brings up the question of the time lag between today's basic research and tomorrow's technology. The engineer is usually concerned with achieving practical results on a relatively short timescale, say one to five years. But often he will not know precisely, beforehand, what areas of materials science he will have to draw on so that a shrewdly developed stockpile of scientific knowledge and the techniques for rapidly acquiring new knowledge are vital for current and future engineering projects. If the knowledge is to be ready when the engineer wants it scientists may have to be working five to twenty years ahead. Thus today's basic research may be the engineer's handbook fifteen years hence. Much of the basic research of fifteen years ago is, in a sense, in the engineer's handbook today.

The occurrence of such timescale effects may be better understood with a specific example, such as provided beautifully by research into the band structures of semiconductors. In the early fifties efforts to find ways to calculate the electron band structures, or energy distributions, in crystalline semiconductors probably seemed rather remote from the tasks of trying to make practical junction devices. But with the aid of the relatively large computers that were beginning to make their appearance such calculations led to marvelously detailed insight into the electronic and optical properties of semiconductors. Calculations were steadily refined and extended to other crystalline materials, but particularly semiconductors. As a result, such phenomena as the Gunn effect and laser action in gallium arsenide and light emission from junctions in gallium phosphide are all understandable in terms of the detailed band structures of these materials. In fact, so well accepted have band structure calculations become that the modern, sophisticated solid state electrical engineer, trying to develop a more efficient Gunn effect oscillator, or a laser, or a light emitting diode, or many other semiconductor devices, would first consider the band structures of available materials. So the esoteric, seemingly remote theoretical solid state physics research of nearly a couple of decades ago is nowadays the base from which an electronic engineer embarks on specific short term development projects.

In what follows, illustrative examples will be given of current opportunities in materials research, both curiosity- and application-motivated.

These examples were extracted from a considerable number of written inputs from those knowledgeable in the field of materials science and engineering.

These opportunities in materials research can be conveniently arranged into four groups:

(i) particular classes of materials,
(ii) materials processing,
(iii) basic properties of materials that are clearly relevant to eventual applications,
(iv) basic properties of materials where the specific relevance is not yet apparent.

CLASSES OF MATERIALS

Ceramics

Polycrystalline ceramics compete with metals and glasses as engineering materials. In the future, as in the past, the major aim of ceramics technology will be the development of new compositions and processing techniques to achieve superior physical and mechanical properties. These properties will be gained through close control of composition, density, and size, shape and orientation of the grain structure. Thus increasing emphasis will be placed on the relationships among composition, microstructure and material properties. The following areas of research are vital to the realization of that aim.

For new compositions, basic study in solid state physics and chemistry is necessary in order to gain new insights concerning electric, optical, magnetic and mechanical phenomena which may be peculiar to ceramics. In the recently discovered lead-lanthanum zirconate titanate ceramic, for example, it was found that the addition of lanthanum to $PbZrO_3$-$PbTiO_3$ resulted in compositions with improved optical transparency, electro-optic memory characteristics and linear and slim-loop quadratic electro-optic characteristics. If the role of lanthanum in relation to these properties is better understood, new ceramics with still better physical properties may be developed. Other examples of opportunities in devising new compositions are found under the section on electronic materials.

In the area of mechanical properties, an improved understanding of the relation of crystal structure and bonding behavior to crystal plasticity, as well as a refinement in the treatment of fracture mechanics coupled with microstructures, could lead to ceramics which are strong and tough. High temperature structural ceramics are receiving increased emphasis as is evident by work on silicon nitride and silicon carbide for gas turbines. These materials exhibit high temperature strength coupled with good thermal shock resistance on account of low value of thermal expansion and high thermal conductivity. Recent studies have indicated that improved properties may be possible in complex systems such as solid solutions of $ß\text{-}Si_3O_4$ and Al_2O_3. In addition, high density could be achieved by sintering at relatively low temperatures. Hence ceramics based on Si-Al-O-N and related systems appear promising as high temperature structural materials.

Other areas of research interest in ceramics include behavior in severe mechanical environments (abrasion, cutting, and ballistic loading), physiological environment (bioceramics) high pressure environment (deep-submergence components) and radiation environments (laser damage, swelling of nuclear fuels).

In the area of processing techniques: (a) More needs to be learned about the chemistry of oxide formation with the exception that this research would lead to novel techniques of preparing high-purity oxide particles of controlled composition and particle size and shape. Such improved starting materials would enable better attainment and control of microstructure in subsequent processing operations. (b) Continued study of the basic mechanisms of sintering, particularly in complex systems of several ceramic components, is a must if the achievements of dense, transparent ceramics made in simple systems are to be extended to new systems. Thermodynamics of phase relations, kinetics of reactions, nature and behavior of surfaces and interfaces, and plastic deformation behavior are major topics in this area. (c) Basic studies of novel processing techniques are of paramount importance. These include extension of hot pressing to forging and other types of hot deformation, as well as computer analysis and control of complex processing variables involving temperature, time, pressure and gaseous environment. Since many physical and mechanical properties of ceramics are anisotropic, attention might be paid to texture development in processing.

Glass

Many "discoveries" have been made in glass science in the last 25 years. In general, these have not been instances of isolated discoveries as such, but rather a continual building on an accumulated body of experimental facts, until a "discovery" or rather an "understanding" was achieved. In this vein continued investigation is needed in such areas as: Kinetics—glass formation is basically a kinetic problem and much more needs to be known about the general mechanisms of glass formation for various types of composition as well as associated dynamic problems including "network" and ionic relaxation (diffusion, conductivity, polarization, etc.). Phase separation —separation of a single phase, homogeneous glass, into two or more amorphous phases, or amorphous and crystalline phases may be either troublesome or useful. The understanding of both the thermodynamics and kinetics of these processes have been advanced substantially in recent years but is not yet at the stage where the occurrence or absence of phase separation in the more complex glasses can be predicted.

Brittle fracture—one of the major drawbacks in the use of glass products is usually rapid deterioration of strength. An understanding of the process of brittle fracture, ultimate strength, "notch" sensitivity and static fatigue, have led to some improvements in useful strength, as well as more efficient use of the inherent strength of glass products, but here again a knowledge of the fundamental limits to mechanical properties has not yet been reached.

Structure—the achievement of an "understanding" of glass structure is difficult as well as difficult to define. The use of new tools (NMR, EPR etc.) should produce much additional knowledge in this area—clarification of the "borate anomaly," recognition of the occurrence and role of pairing and clustering and elucidation of the character of site distortions, for example.

Electronic Properties—studies of "electronic" behavior have led to such discoveries as the switching and memory effects in amorphous semiconductors. Studies of the behavior of 3d and 4f ions in glassy hosts has produced structural information as well as an understanding of the physics of optical absorption and fluorescence in glassy solids. But in view of the increasing role expected for glass in electronic applications such as optical communications, there is a need for greatly improved understanding of the spectroscopic properties of various ions in various glassy hosts.

Optical waveguides—A particularly demanding and exciting challenge to glass technology is the development of practical long-distance optical waveguides for communications. A commonly envisaged configuration is a clad optical fiber with a high refractive index core and a low refractive index cladding. The realization that the fundamental limits to loss mechanisms in some inorganic glasses in the red and near infra-red spectral regions should be only a few dB/km has led to intense activity aimed at the preparation of glass fibers of extreme purity, extreme freedom from light scattering and absorbing defects, and extreme dimensional control. Such needs have emphasized, in particular, how crude the present state of technology is in the area of ultra-purification of chemical compounds—for all but a handful of materials there is no counterpart to the elegant zone refining process.

Metals

A continuing challenge to basic research in metals is to discover alloys capable of meeting exacting performance criteria under ever more hostile environmental conditions, such as those used in jet engines and in nuclear reactors. Much exploratory effort remains in the search for high-field superconductors with high transition temperatures. In the complex world of microelectronics, thin film metallization plays a central role, along with attendant problems in short circuit diffusion, electromigration, corrosion resistance, etc. associated with thin surfaces. A large class of metals and alloys acts as "contacts", as in switches, relays and commutator brushes. Wear, tarnish and electrical erosion are some of the perrenial problems. These topics are discussed below as illustrative examples of metals research.

Many of these are related to high performance technologies and thus call for much effort in broad “alloy mapping” programs. It is recognized that steady improvements are also expected in conventional ferrous and nonferrous alloys. The most promising lines for progress for these materials, however, seem not to lie so much in broad “alloy mapping” programs as in devising more efficient and economical processing techniques, as discussed in a later section. These processing techniques are to be based on knowledge of material properties and behavior gathered over the last several decades.

Superalloys

Alloys based on nickel, cobalt or iron which are intended for service above 1000ºF are frequently termed superalloys. The nickel-based system is the most advanced and most widely used of these alloys in current aircraft gas turbine engine applications. A major contribution to high temperature creep strength is derived from a high volume fraction of very fine coherent, ordered ?' precipitates, which are stabilized by alloying additions based on considerations of low diffusivity, low interfacial energy or low solubility. In addition, the grain structure may be stabilized with insoluble phases, carbides or oxides. Further improvements in superalloys appear probable from two directions: One based on overcoming temperature limitations resulting from environmental attack; the other on increasing strength from processing improvements. There is also a need for improving the correlation between simple laboratory tests and service conditions so that life of components can be predicted with greater accuracy.

The next generation of superalloys will operate at temperatures that are too high for the traditional Cr_2O_3 protective scales, because evaporation of chromium via CrO_3 takes place to an increasing extent above 1800ºF, requiring the use of relatively brittle coatings. One promising direction is to develop a new family of superalloys protected by Al_2O_3 scales, which are not subject to evaporation, and grow very slowly, because of the low cationic diffusion of $A13^+$ through the scale. Al_2O_3 scales tend to spall during thermal cycles, but this may be overcome by dispersed oxides, which may be added intentionally as in the TD alloys (thoria dispersed) or formed by internal oxidation of reactive elements like yttrium. It has been discovered only recently that oxide dispersions have significant beneficial effects on high temperature corrosion in addition to their well-known beneficial effects on high temperature creep. The rate of scale formation is much lower, and the adherence of the scale is greatly improved. The dispersed oxides reduce the reactive alloying content (like chromium) needed to produce external scales rather than internal oxides. There is also evidence that the improvement in adherence is due to the internal oxides acting as vacancy sinks, preventing vacancy agglomeration into voids at the scale-coating interface. Thus, major questions to be answered in the development of coatings include: effect of alloying additions (1) on the diffusivity of the alloy constituents; (2) on the thermodynamics and kinetics of formation of competing oxide films; (3) on competition between internal and external oxidation; and (4) on vacancy behavior and its possible role in spalling.

Processing is a major arena for improved properties and performance of superalloys, particularly through the use of directionally-solidified eutectic alloys, electroslag remelting, composite structures joined by diffusion bonding, and improved powder metallurgy processing. Mechanical alloying in attritor mills can effectively disperse oxide phases. Control of recrystallized structure to produce interlocked, elongated grains aligned in the stress direction can be provided by control of dispersed phases or through zoned recrystallization. The high temperature benefits resulting from elongated, interlocked grains in nonsag tungsten can be extended more broadly to superalloys and other high-temperature materials.

In alloy development for still higher temperature service, there is an attractive possibility for new class of alloys based on the refractory metals. Major problems are similar to those for superalloys (protective coatings, optimum alloying and processing), but only more so at the present time.

Radiation Resistant Reactor Materials

The operating conditions within fast breeder reactors, i.e., high temperatures (~575ºC) and high neutron fluxes, impose very stringent materials requirements; the materials requirements for a fusion reactor system are still more severe. Under these conditions swelling of the reactor components, resulting from the formation of voids, leads to dimensional instability of the structural components. In order for reactors to compete favorably with conventional energy sources, the reactor system should have as long a life as possible. To find out how to control swelling phenomena is of high importance.

During neutron irradiation, self-interstitials and vacancies are produced in equal numbers in structural materials. However, interstitials are preferentially removed from solution leading to the super saturation of vacancies which, under the right conditions, precipitate as voids. It is, however, clear that each of the following metallurgical variables have an effect on the formation of voids: (i) impurities, (ii) irradiation dose and temperature, (iii) dislocation density and distribution, (iv) fine precipitates and (v) grain boundaries. Metals and alloys containing second phase particles may be more resistant to swelling. Since the operating temperatures are fairly high, superalloys and refractory metals and alloys are the best prospects for satisfying the stringent material requirements. In fusion reactors the walls must be compatible with lithium, sputtering, fast neutron damage, and higher temperatures. The ductility of refractory materials is often insufficient for fabrication into complex shapes. Either the ductility of these materials has to be improved or new fabrication techniques developed. Another factor which needs investigation concerns the use in fast breeder reactors of liquid sodium and liquid sodium containing dissolved gases.

Superconductors

One area posing a great challenge to metals research is the development of practical superconductors of possible use in thermo-nuclear power generation, high-speed transportation, propulsion, magnetic-ore separation, secondary water treatment, and desulfurization of fuel oil and coal. There is a need for research aimed at translating the broad theoretical guidelines of solid state physics, such as the need for high density of states and large electron-phonon interactions, into available material parameters such as chemical composition, crystal structure, elastic constants, lattice parameter, and melting points. Thus far transition-metal compounds with the beta-tungsten and rock-salt structures (at room temperature) have yielded the highest superconducting transition temperatures (T_c). It has been found, however, that certain phases of materials like Mo-Re, and more recently, Nb_3Ge, which are stable at elevated temperatures but metastable at room temperature, also exhibit high T_c. If new high T_c materials turn out to be metastable phases, there will then be a major challenge of processing these materials economically. Indeed, uneconomical processing is a major problem preventing the wide-spread use of known high T_c materials such as Nb_3Sn. The compound Nb_3Ge has the highest known T_c of 23.2ºK, but a method of fabricating it into useful shape and retaining the high transition temperature has yet to be devised. Since stoichiometry and atomic order are two critical material parameters, basic research in phase equilibria and kinetics of phase transformations is a necessary prelude to new or improved processing techniques. Concerning the goal of raising the critical current density, there is still much need for detailed fundamental understanding of the role of various imperfections such as inclusions, dislocations and grain boundaries in pinning the flux lines. Such understanding should lead to substantial improvement in critical current density through structural control by processing.

Contact Materials

The life and reliability of an electrical contact is ultimately limited by one or more of the following phenomena; arc erosion, tarnish film formation, polymer formation, wear or particulate contamination. Which one or combination of these eventually determines contact life depends on the circuit parameters, the contact material (s), and the chemical and mechanical environment of the contact. Contact failure is generally characterized by the development of excessive contact noise and/or resistance.

In spite of the complexity of this subject, opportunities for fairly well-defined materials research on contact materials do exist. The first such area is that of tarnish film formation. Tarnish film formation is the limiting failure mode in many low-energy or dry circuits involving switching or semipermanent contacts. Gold- or platinum-group-based alloy systems have been the traditionally-preferred contact materials in these instances because of their limited film forming tendencies. Research directed towards limiting film formation on less noble or base metal alloys exposed to nominal contact environments would appear worthwhile. Oxide and sulfide films are those of principal interest.

A second area is that of the arc erosion behavior of contact materials, particularly as used in low- to medium-energy circuits. Here, the objectives are to understand those properties of a contact that determine arc duration and energy and which lead to lateral as opposed to localized erosion. Studies over a range of well-defined circuit conditions are required here.

Additional research opportunities exist with regard to frictional polymer formation, mechanical wear of contacts and the reaction of mercury with contact support and contact materials in mercury-wetted contact systems. These areas, however, are judged to be of lesser overall importance than those of arc erosion and tarnish film formation.

Plastics

Substances, such as cotton, wool, and silk have been known to mankind longer than recorded history. Others such as rubber, rayon, and celluloid were developed for practical use through empirical processes long before their basic molecular character was correctly known. But the single important feature that sets these seemingly unique substances with remarkable physical and chemical properties apart from a host of well recognized materials is that they are made of very big molecules which obey all the recognized chemical and physical laws but which have added properties that stem from their giant size. Intense research has yielded knowledge of how variation in the structures of these giant molecules, through new approaches in chemical synthesis, can be invoked to cause valuable changes in physical properties. Fundamentally, these marcomolecules, both natural and man-made, consist of chemical combinations of small molecular entities, monomers, that are part of the huge family of chemical compounds. It is the combined effect of the monomeric structures that determines the physical and chemical character of the polymer. While research along these lines began 40 years ago, it remains a vital, increasingly sophisticated part of chemical science.

During the past decades a wide variety of new and useful polymers have been brought into commercial production. More new polymers with interesting mechanical, electronic and chemical properties will undoubtedly be produced in the future but launching a radically-new polymer is expensive. Semi-empirical routes to useful materials are likely to be followed most often, one of the most attractive of these being to explore the effects of blending of polymeric materials available at present. The properties of polymer blends are not merely the means of those of the two individual components. The resultant properties depend on a variety of factors including, perhaps most importantly, the intimacy or heterogeneity of the mixing. The degree of dispersion can however vary greatly and indeed some polymer pairs cannot be properly blended at all. Where blending of pure polymers is impossible various modifications may be made to improve compatability. As a known example the rubber particles used to increase impact strength in ABS (derived from Acrylonitrite-Butadiene-Styrene) are surface modified by grafting to provide a good bond across the boundary.

Increased fundamental understanding of the properties of blends is needed to enable us to readily obtain materials with a wide range of properties, properties which are sometimes too specialized to warrant bulk production of a new polymer. Furthermore, combinations of properties not possible with single polymers will be achievable using blends, not only of two polymeric components but several. This need for research and exploration in the field of polymer blends can be compared in many ways to the history of metal alloy research and development.

Several important research activities will illustrate this continuing appear for increased understanding of molecular structures and physical properties. Major achievement and continuing effort occur in the field of rubber-like compounds. Nature has given us, in the product of the rubber tree, a molecule that possesses a high degree of flexibility. This property is partly owing to the nature of the chemical bonds in the molecular chain, which are relatively free in their movement. The flexibility also stems from the structural asymmetry of the monomers which constitute the chain. This asymmetry keeps the chains from clustering closely and thus allows the freedom of motion that is essential to rubber-like behavior. Research into the synthesis of polymers possessing the attributes of natural rubber was a critical activity in the logistical efforts of World War II. With the growth of new knowledge of the control of synthesis, fundamental studies can develop new, superior forms of rubber-like compounds. The new family of polymers made from ethylene and propylene is a recent example of achievement of rubber-like properties through exploration.

All rubber-like substances lose their visco-elastic properties and become far more rigid when the temperature is sufficiently reduced. These materials are then glassy in character and behave as almost perfect elastic solids. There is a host of polymers that are glassy at ordinary temperatures. As with the inorganic glasses, many of these materials are valuable for their optical properties. Fundamental studies with monomers or combinations of monomers to yield polymers with desired properties, such as a chosen optical absorption or refractive index, have been and can be expected to be highly productive.

A striking achievement in polymer science has been the discovery of controlling the structural regularity of polymer chains. This chemistry of molecular shape, sterochemistry, is making possible the synthesis of highly-ordered molecules which, by virtue of their symmetrical character, are able to cluster into crystalline order. It has been found that the individual crystalline regions are extremely small but highly organized, and that they form a superstructure or morphology which confers strength and dimensional stability to the polymer somewhat analogous to ways in which precipitates can lead to strengthening of metal alloys. Recent research has shown that the morphology, although extremely complex, is nevertheless governed by identifiable factors, such as the rate of the crystallization and the distribution of molecular sizes. Further research in this area will undoubtedly lead to new practical materials.

The relations between molecular structure and physical properties is central to the behavior of polymers of biological interest. The proteins responsible for form and strength in much of living matter, notably collagen and Keratin, are examples of substances in which these relations are now becoming well understood at the molecular level. Continued research in this area is likely to benefit both inanimate and biological or medical applications for plastics.

Although similar in many ways the plastics and rubber industries differ in one major respect—processing. Conventional rubbers must be compounded with fillers and curatives, molded and cured, whereas thermoplastics in general require less compounding and no curing. Recent developments in block copolymers have led to the synthesis of elastomers in which the crosslinks are formed through association of the more rigid sections of the polymer chain. They are thus physical rather than chemical in nature and may be formed and broken reversibly by heat. These new rubbers have the potential of being processed as plastics. The early members of the class show creep rates which excluded them from many applications but an appropriate choice of the component monomers, together with the development of appropriate polymerization techniques, should lead to commercially-useful rubbers.

What is likely to be one of the most important and active areas for polymer research in the immediate future concerns their durability. Fluoropolymers and poly (methyl methacrylate) have excellent resistance to weathering, but other polymers destined for outdoor exposure require protection against ultraviolet degradation. Polyolefins, natural rubber, poly (vinyl chloride), polystyrene and cellulose derivatives are especially vulnerable to deterioration. Protectants function as light screens, ultraviolet absorbers or deactivators. At elevated temperatures the polyolefins, natural rubber and cellulose materials are stabilized by antioxidants that destroy hydroperoxides and inhibit radical chain reactions. Hydrocarbons in contact with transition metals are also protected by sequestering or chelating agents. Various basic metal salts are added to poly (vinyl chloride) to suppress discoloration and neutralize hydrogen chloride. Current studies center on stabilizer interactions, retention, and life-times under various conditions. Minor structure modifications have recently produced marked improvement in the stability of poly (vinyl chloride) and polyoxymethylene without significant changes in physical properties. Further increases in stability probably can be expected from additional changes in molecular structure of polymers.

Composites and Concrete

A composite material generally is defined as a combination of two or more mutually-insoluble macroconstituents differing in composition or form. The microconstituents may be glass, plastic, ceramic or metal. One normally thinks of composites, however, in a more restrictive sense, as high-modulus reinforcing fibers (most often glass) supported in a thermoset resin matrix (generally epoxy or styrenated polyester). Glass fiber reinforced thermoplastic resins (RTP) are also finding increased usage in structural applications, particularly in the automotive field. New high-performance fibers—boron, carbon (graphite) etc.—with still greator modulus are available, but only at prices that preclude widespread commercial use at this time.

The development of sheet molding compounds (SMC) and bulk molding compounds (BMC) shows promise of enlarging appreciably the scope of application of these composites, particularly in the transportation field. The pultrusion process has already had an impact on the economical fabrication of structural shapes for use especially in the chemical process and electrical industries. The former is an important major field for adoption of composites, but the chemical resistance of the resin and of the resin-glass interface are possible constraining factors.

A large potential market also exists in construction, but here certain material shortcomings become apparent. For example, flammability needs to be reduced by the use of halogen-containing raw materials or other fire-retardant additives, but these add to the cost and generally degrade weatherability. Weatherability, in turn, can be enhanced by laminated coverings of poly (vinyl fluoride) film or suitable paints, but these too add to the cost and offset the advantages of integral color and surface texture inherent in composites. Unitized bathrooms are now molded from these materials but durability becomes a question because of their rather poor scratch and mar resistance.

True structural applications for composites become feasible, for example, for high-performance aircraft, only with the use of the newer but more costly boron and graphite fibers. Entire aircraft structures based on epoxy-glass have been made for small private planes, but this remains a minor application at present. In any case, the lack of adequate design data (including the incorporation of anisotropy of properties in aligned composite), understanding of failure modes, and the high cost of suitable materials hamper the more rapid expansion of aerospace uses into commercial aircraft.

Major needs in the exploitation of composite materials are for attention to such factors as: raw materials cost; low-cost; high-speed manufacturing techniques; modulus and ductility; flammability; weatherability; and suitable design data. Expanded use of the newer, high-performance materials should develop ultimately as increased demand leads to lower materials costs.

In addition to realizing their application in aerospace due to an improved strength-to-weight ratio, composites can be expected to see increased use for improvement of other physical properties not attainable with individual components. An active area for research concerns all-metal composite strip and wire. Two- and three-layer composites are available and widely used but there is need for five-layer composites (e.g. outer, corrosion-resistant, joinable layers, inner strength layers and a high-conductivity core). These are not currently exploited because of their high cost derived from low yields, but improved methods of fabrication and yield could stimulate their use. Other examples of potential uses for composites are in copper-clad superconducting filaments for increased critical current carrying capacity, fiber reinforced or dispersion strengthened copper for combination of high strength and electrical conductivity, fiber reinforced magnets for creep-resistant high temperature rotors, and the possibilities of using directionally-solidified eutectics for magnetoresistance, electromagnetic and radiation detector applications.

Three major areas of research are needed to broaden the future use of composites. First, study of reactions between fiber or dispersant and matrix (e.g. phase equilibria and kinetics of phase transformations, surface reactivity) and wetting. This study should lead to improved adhesion between fiber or dispersant and matrix and to retention of individual characteristics of both components, thus permitting the attainment of property improvements expected from theory. Secondly, research on fiber and whisker growth, particularly fibers oriented for subsequent processing. Also important are innovations in handling of fibers to maintain orientation and prevent breakage, as well as new techniques of joining. This area of research is necessary for improvement of processing of composites starting with separate components. Finally, since there is economical advantage in fabricating a composite using a single operation, further research should be conducted in directional solidification of eutectic systems and in directional alignment of precipitates and other dispersants in the solid state. Rheocasting may offer a new method of producing matrix-dispersoid systems.

Perhaps the most widely-used composite is concrete, the single most-used, man-made construction material. Because it is a rather complex composite, basic research into the properties of the constituents and their interrelationships is an absolute necessity to fill the ever-expanding demands of construction. The following areas for materials research are noted.

Cements

Basic research on the physico-chemical properties as a function of composition will enable the custom development of cements designed for specific functions. These include expansive cements for shrinkage control or for self-stressing, cements with controlled setting time, and cements with improved resistance to weathering and to physical, chemical and thermal attacks. Particularly challenging areas of research include studies of basic properties of admixtures and chemical reactions among them as well as with aggregates and reinforcement materials.

Aggregates

Basic studies conducted on the replacement of stone with light-weight material will improve the strength-to-weight ratio of concrete and permit increased use in tall buildings and long spans. These aggregates include waste products such as fly ash and other recycled products. They also include other natural aggregates indigenous to local construction sites for obvious economic reasons. Again, the physico-chemical properties of these materials in relation to the other constituents in concrete need to be studied thoroughly.

Reinforcement

Reinforcement materials such as steel are used to increase the tensile strength of concrete. Studies of adhesion and reactivity of steel with cements and admixtures of controlled composition are important to prevent strength degradation. In addition, alternatives to the conventional steel bars, such as chopped steel fibers and organics-coated glass fibers, need be pursued to broaden the scope of use offered by the reinforcement constituent of concrete.

In short, concrete is a complex composite of several constituents. The introduction of any single constituent will affect the properties of the other constituents. Hence the challenge in basic research lies in terms of the broad interrelationships among all constituents.

Electronic Materials

The term electronic materials embraces a wide variety of active materials which are usually and conveniently labelled according to their electronic property of practical importance. These include semiconductor, optical, magnetic, piezoelectric, photochromic, etc. materials. The central position in electronic materials is occupied by:

Semiconductors

Semiconductors are the heart of solid state electronics. The fundamental properties and other materials aspects of the elemental semiconductors, silicon and germanium, are now very well established but much more work needs yet to be done to achieve even greater control over the impurity and defect content of crystals of these materials. The influence of defects and impurities becomes proportionately greater as the dimensions of devices, integrated circuits, and so on, become smaller and smaller. Crystal perfection is also important for high voltage power applications.

Explorative work on group III-group V semiconductors (such as GaAs and GaP) as structural and electronic analogs to the group IV semiconductors (Ge and Si) started in the 1950’s. During the 1960’s several important new devices based on these materials made their appearance, such as microwave oscillators and varactor amplifiers, electroluminescent diodes and injection lasers. Fundamental understanding of these materials is well along but much more needs to be done on the solid state chemical aspects and on defect, impurity and stoichiometry control. Recently, complex ternary III–V compound structures for injection lasers based on $Ga_{1-x}Al_xAs$, have been developed to a high point of precision using liquid-phase and molecular-beam epitaxy.

The explorative front in semiconductor materials is probably now centered on ternary analogs of the group IV and III–V semiconductors. The II–IV–V_2 compounds e.g., $CdSnP_2$, have received considerable attention. Their band structure has been shown to be very similar to that of the III–V compounds and their electrical properties have been investigated. However, defect, phase and thermodynamic investigations are very scarce. The I–III– VI_2 compounds (e.g., $CuGaS_2$) are also receiving attention. It has been shown that their band structure is similar to that of the II–VI compounds. The copper compounds investigated have shown p-type conductivity in contrast to the II–VI sulfides and selenides. All I–III–VI_2 compounds investigated so far have been found to have direct band gaps. In several materials, visible stimulated emission has been observed at low temperature. These various properties might allow the design of heterojunctions involving n-type II–VI-sulfides and selenides. Such structures might be expected to emit visible light and exhibit laser action; a particularly pressing need is for an efficient blue electroluminescent diode. Much work remains to be done on these materials, both on their physical and chemical properties. Furthermore, the techniques for the controlled preparation of single crystals is still rather primitive. Phase diagrams are generally not known, especially for the more promising compounds like $CuGaS_2$ and $CuAlS_2$. An even bigger problem is the defect chemistry, which is more complicated but may provide more possibilities than for binary compounds. Thermodynamic investigations are virtually nonexistent. While some experimental band structure investigations have become available recently, the more detailed nature of valence and conduction bands are unknown and it is conceivable that some of these materials might be well suited for certain devices like Gunn oscillators.

Recently there has been a marked increase in theoretical and experimental studies of amorphous semiconductors. This interest is due, in part, to the electrical switching effects that have been observed in these materials but more generally to curiosity about the effects of a lack of long range structural order on physical properties. Theory has predicted that, upon going from the regular three-dimensional structure of a crystal to the disordered structure of an amorphous solid, the electronic structure changes from that of a normal band model to that of band edge tailing (smearing of band edges) and the localization of states in the gap. Because of coulombic repulsion, a fraction of the highly localized states will be singly occupied (unpaired). However, theory is not yet able to predict quantitatively the concentration, degree of localization, and the energy spectrum of these states; nor the fraction singly occupied. There is considerable question whether experiments will confirm the theoretical models. Experimental studies have included transport (conductivity, field effects, thermostimulated currents, drift mobility), optical, magnetic susceptibility, and spin resonance, but results thus far are often ambiguous or conflicting.

Some properties can be markedly affected by introducing structural disorder. For example, there are glass compositions which are 10–11 orders of magnitude more resistive than the corresponding crystal. Because of the ability of glass-forming materials to transform fairly reversibly between the glassy and crystalline states and the associated changes in electrical conductivity and optical properties, amorphous semiconductors have been suggested for use as electrical and optical memories. At low temperatures, the electrical conduction properties appear consistent with a hopping transport process between localized states. At fields exceeding about 10^4 V/cm, amorphous semiconductors suffer an electrical instability which results in a switching effect. It is not yet fully resolved whether this instability is triggered by an electronic mechanism, a thermal mechanism (thermal avalanching) or a combination of the two.

The interpretation of optical effects is hindered by the lack of a detailed theory of absorption in amorphous materials. However, localized states in the gap are expected to produce absorption effects at energies below the absorption edge. Experimentally, absorption tails are observed but they are both structure and impurity sensitive and distinguishing fundamental from such secondary causes of absorption tails is proving to be a very difficult challenge. Experimental results can often be interpreted as due to the presence of inhomogeneities or impurities. As an example: Is the observed spin resonance in Ge, Si and SiC due to unpaired localized spins in the amorphous matrix, or due to surface states at the surfaces of internal voids? Likewise, the observed frequency dependence of the a.c. conductivity, and the field dependence (super ohmic) of the d.c. conductivity, can be interpreted in terms of a carrier hopping process in the matrix, or interpreted as due to structural and chemical inhomogeneities. Clearly, in future research, materials preparation and characterization, including chemistry (impurities), homogeneity, and structure, must achieve the level of sophistication of that currently done on crystals. In this area there is much to be done.

Magnetic Materials

Magnetic materials embrace metals and alloys on the one hand and single crystal or polycrystalline insulators on the other. There are two major opportunities in the future of practical magnetic metals and alloys. First, in the search for materials with improved magnetic properties there is much need for basic understanding of various magnetic phenomena such as saturation magnetization, magnetocrystalline anisotropy and magnetostriction and the development of guidelines relating the phenomena to available material parameters such as composition and crystal structure. Secondly, there is need for understanding the relationship between microstructure and the technical magnetic properties (e.g. permeability, remanence, coercivity) to be exploited, so that economical processing techniques can be developed for fabricating the materials into useful devices.

Permanent magnets—Permanent magnets of alloys of cobalt with rare earths have yielded energy products and coercive forces superior to those available in the past. There is need for understanding the structure and phase relations in these permanent magnet compounds so that more economical processing techniques can be devised. In addition, research on the origin of high magnetocrystalline anisotropy energy, which is chiefly responsible for the large coercivity of these magnets, in relation to composition and structure may yield other and superior permanent magnet alloys.

High temperature magnets—Magnetic materials may be used as rotors in electric generators that operate at elevated temperatures. Hence there is a need for materials with high magnetic flux density together with high mechanical strength at the operating temperatures. Studies on the role of dispersoids and composites in magnetic and mechanical hardening would be useful in optimizing both properties.

Giant magnetostriction materials—Metals and alloys with large magnetostriction can compete with piezoelectric materials as transducers often with the advantage of being ductile and tough. Giant magnetostrictions ($\sim 10^{-3}$) have been recently reported in rare-earth transition metal compounds, but these values are gained only at large applied magnetic fields. Some are also brittle and pyrophoric. A better understanding of the origin of magnetostriction may lead to more practical alloys.

Magnetic recording materials—Metallic particles such as Co-Fe and Co-P exhibit greater magnetic moment and high Curie point compared with iron oxide. There is need here for a more economical mass production of these fine particles if they are to compete with existing oxide technology.

Magnetooptical materials for information storage—Compounds such as MnBi and MnAlGe are being evaluated for information storage using Curie point writing techniques employing laser beams. There is much need for studying the microstructure of these compounds, particularly in thin film form. Also needed is a search for other materials exhibiting large Kerr and Faraday effects. As yet the magnitude of these effects cannot be predicted from a knowledge of composition and crystal structure.

Amorphous magnetic materials—alloys such as Fe-P-C have been prepared in the amorphous state and shown to be ferromagnetic. There is recent indication that amorphous Co-Gd films exhibit uniaxial anisotrophy and “bubble” domain behavior. Amorphous chalcogenide films might prove useful in optical storage systems. Study of the structural origin of intrinsic parameters such as saturation magnetization, magnetic anisotropy and magnetooptical coefficients could thus lead to the development of a new class of magnetic alloys.

Conventional magnetic materials—Because of the large volume in use for conventional magnetic materials such as silicon iron, even small improvements could lead to large savings. One recent example is the commercial development of highly-oriented, Goss-textured silicon iron using aluminum nitride needles to restrain normal grain growth. The sharper texture leads to higher initial permeability. By applying a surface coating which produces tensile stresses on the strip, magnetostriction and total loss are decreased.

Dissipative losses, such as those caused by eddy currents in magnetic metals, are generally too large to permit their use as inductors at mega-hertz frequencies. As a result an interest in the insulating magnetic oxides arose in the late 30’s, culminating in the development of inductor and permanent magnet ferrites in Japan and Holland. Work subsequent to World

War II has seen marked advances in permeability and quality and extension of the use of inductors to frequencies approaching a gigahertz. The ferrites have also found applications as memory elements, as microwave components (to >50 gigahertz) and as low cost permanent magnet materials for closing refrigerator doors and (hopefully) magnetic levitation of high-speed trains. More recently single crystal films of magnetic garnet deposited on a nonmagnetic matching substrate have become of interest for miniature memory and logic (bubble domain) devices. These developments rest firmly on a basic understanding of the physics of magnetism and on magneto-chemistry.

Clearly, there now exists a need for even better inductors and higher coercivity permanent magnets. To achieve these ends more subtle control of the properties, subdivision and orientation of particles in dense compacts must be realized. Controlled inhomogeneity can be of particular importance in inductors. In contrast, inhomogeneity is to be avoided in the thin garnet film technology. Here defects must be avoided, film uniformity in composition and thickness must be preserved and allied skills in crystal preparation, processing, masking, etc., must be optimized. Research, in chemical additives and preparative techniques, in new flux systems for liquid phase epitaxy film growth and control of chemical vapor deposition processes are expected to provide some of the needed technological advances.

Improvement in our detailed understanding of dynamic processes such as the physics of domain wall motion can be expected to increase markedly the technological properties of magnetic materials. Improved understanding of less than three-dimensional solids—metal organic cluster complexes, layer and chain compounds will provide new insights into magnetic interaction with improved materials as an output.

Optical Crystals

The demonstrations of maser and laser action in solids count as great events in materials science. The laser in particular has been developed into an important energy source for micromachining, for drilling dies, adjusting microcircuits, trimming resistors, etc. It has also found application in telemetry, range-finding and ordnance. However, its full potential for low cost, broad-band communication has yet to be realized.

The present high level efficiency in optically-pumped lasers rests on two scientific cornerstones—a detailed understanding of the spectroscopy of the rare earths and an understanding of the influence of the host crystal on spectroscopic linewidth, in particular the role of mass action interactions in charge compensating Nd^{3+} when it is present in sites of different valence. Trivalent Nd is thus the most favorable host environment for low threshold lasers at present, further research might lead to more economical performance in other host materials which admit to stronger Nd^{3+} optical absorption bands more favorably with respect to 0.93μ, the pump wavelength available from gallium arsenide laser diodes.

The potential use of lasers in communications systems has stimulated intense searches for efficient nonlinear optical materials useful for modulators, amplifiers, frequency mixers, and so on. Interest has centered particularly on ferroelectric classes of large, band-gap crystals for use in and near visible wavelengths and on ternary semiconductors for use in the infra-red. These materials were discovered mainly using structure and polarizability as search criteria. Although present theories now readily account for the optical susceptibility of materials, detailed a priori predictions of nonlinear optical properties are still not possible. The need for quantitative prediction of susceptibilities should provide stimulus and motivation for a fundamental approach based on chemical bonding and structural considerations. Perhaps materials science has more closely approached the ideal of permitting “molecular engineering” based on fundamental knowledge in this sphere than anywhere else to date.

The systematic study of nonlinear effects may also provide important new structural information and details concerning polarization and bonding that can give insight into interactions between amino acids and other materials important to life. Indeed the measurement of susceptibilities provide one of the few direct measurements of the polarizability of electrons in bonds available to the chemist.

From the fabrication viewpoint there is a need to develop ways of miniaturizing optical integrated circuits, through controlled epitaxial growth and other thin film processes. In addition, improvement in crystal preparation techniques to minimize nonuniformities, defects, etc. are needed. These improvements can be expected to flow from an understanding of the hydrodynamics of crystal growth, phase equilibria and the connection between the physical chemistry of growth and the physical and chemical perfection of grown materials.

Dielectrics

Piezoelectrics, especially quartz, were among the first electronic materials utilized and one of the triumphs of materials synthesis is the large scale preparation of quartz. Detailed understanding of the physical chemistry of the growth process and the partition of impurities has allowed the growth of quartz superior to the natural material under economic conditions. Lithium tantalate has recently been shown to be a practically useful piezoelectric and a wide variety of new materials are being investigated for stress-optic and surface-wave applications. An improved quantitative atomic understanding of piezoelectric and acoustic effects could be expected to have important device impact by pointing the way to superior materials.

A related topic receiving increasing attention both because of its usefulness in understanding the behavior of polar crystals and because of its applicability to infrared detection and imaging devices is pyroelectricity. Measurement of the pyroelectric coefficient yields valuable information on spontaneous polarization, phase transitions, piezoelectric switching and domain kinetics. The polar materials which are also useful for nonlinear optics, ferroelectric ceramics, and sheets of polyvinyl fluoride polymers are all of interest. High frequency current measurements in pyroelectrics enable a direct study of nonradiative electronic and vibrational relaxation times. At very short times a second effect due to the change in dipole moment of the excited center has recently been demonstrated. These excited state dipoles contribute to a macroscopic polarization change only in pyroelectric crystals, and intense electrical pulses as short as 6 picoseconds have been generated with the mechanism using picosecond optical pulse evaluation. At the present time measurements of excited state dipole moments and nonradiative relaxation times have been made only for a few transition metal ions in $LiNbO_3$ and $LiTaO_3$ but these experiments may be extended to any absorbing center (ionic or molecular, electronic or vibrational) in any pyroelectric host. Using suitable input frequencies or short pulses, intense radiation from d.c. to submillimeter wavelengths can be generated and should enable the study of fundamental, short-life processes which cannot be reached by other techniques.

Photochromic and Electrochromic Materials

Color changes induced in materials by the action of light or electric fields can be useful or a nuisance. They can be used for light-responsive sunglasses and for holographic optical memories. Contrariwise, light-induced optical absorption changes may seriously impair the performance of both passive and optical devices or cause undesirable changes in appearance. Optical “damage” in nonlinear optical crystals due to laser radiation has been ascribed to optically-induced valance changes in impurities in the crystals, analagous to the role of F-centers in alkali halide crystals. Coloration changes in barium-sodium-niobate-crystals have been related to the degree of off-stoichiometry in the crystal. But in most cases the specific mechanisms of photochromic effects have not been established. For many applications it is desirable to have reversible photochromicity, using two different wavelengths of light. Such photochromics are usually slow, however, because for each color center created one photon is required. An area for future research is for a reversible photochromic with gain, i.e., many color centers per photon. This is possible in some irreversible systems at present—(some polymers and the photographic plate being notable) and would lead to greater sensitivity.

Electrochromic materials are receiving increasing attention. These are generally long chain, highly polarizable molecules which can be oriented by an electric field. The electrochromic nature of the molecules leads to an electrically-controllable color change, potentially useful for visual display devices. Electrochromic effects have been observed in dyes—but the effects are fairly small though potentially of interest for electrically-tunable dye lasers. Large effects (~1000Å) are observed in long molecules.

Monolayers of these molecules can have electrochromic electron ratios of 500:1 over a large spectral bandwidth. Applications of such materials to devices calls for fast electrochromic response with a large extinction ratio. The present problem is that generally the longer the molecule the slower the response but the larger the extinction ratio.

Miscellaneous Materials

Solid Electrolytes

Conventional lead-acid storage batteries pose an intriguing challenge to the materials scientist and materials engineer to try to develop more compact, rugged, all solid state batteries using solid electrolytes. Solid electrolytes can be broadly grouped into two mechanistic classes: 1) Defect conductors, such as ßAgI, $CaO \cdot AO_2$ (A=Zr, Hf, Th, Ce) and $M_2O_3 \cdot ZrO_2$ (M=La, Sm, Y, Yb, Sc) in which interstitials and/or vacancies are the ion-conducting species; 2) Disordered cation structures, exemplified by the modified AgI compounds such as $RbAg_4I_5$ and aAg_3SI, and the various ß-Al_2O_3 phases. This second class can be subdivided into two groups: a) the modified AgI phases which are "tunnel" conductors, in which the sparsely-occupied silver sublattice sites are arranged into essentially one-dimensional tunnels which are located parallel to each crystal axis in the various unit cells. b) the ß-Al_2O_3 phases which have the cation (Na, K, Ag, etc.) sublattice sites arranged in two-dimensional layers parallel to the a and b crystallographic planes.

The defect conduction phases are of little interest for solid state battery development because of their low conductivity at ordinary temperatures. In the second group no really optical ionic conductor has been found. The layer structures are suitably conductive but the two-dimensional materials are inherently fragile in the wrong (a and b) direction in the single crystal form, and have drastically lowered ionic conductivity as polycrystalline ceramics.

On an a priori basis, a tunnel conductor would be ideal, but the only known high conductivity tunnel structures are based on AgI—an inherently high cost, low energy system. The pertinent questions are: 1) What is special about AgI? 2) Are there any other compounds with the same special properties of AgI and can they be used to synthesize new electrolytes?

Silver iodide (stable above 146ºC) has the highest ionic conductivity of any solid not close to its melting point. Its crystal structure is curious in that it has both tetrahedrally- and octahedrally-coordinated Ag sites, and is of significantly lower density than the tetrahedral AgI structure. It is this anomalous low density, combined with tetrahedral cation vacancies with shared faces that is typical of all AgI-type conductors. Moreover, if a small mol fraction of a 6-coordinate binary compound (e.g. RbI, etc.) is combined with AgI, a highly ion-conductive ternary solid is formed which is stable at room temperature—i.e., $RbAg_4I_5$. The tetrahedral sites in these ternary structures are somewhat distorted in order to accommodate both the mixed coordination and also the wide differences in density between the two binary parents. It is this ability to withstand considerable distortion of the tetrahedral coordination sphere ("softness") without a large energy increase (which would destabilize the structure) that permits the freakish, low-density AgI-type conductors. Measurements of this property of softness for AgI may lead to other potential binary parents. Other soft binaries appear to be MgSe and MgS; and $Ba_xMg_{6-x}Se_6$ has been shown to be a member of a class of solid state Mg^{++} conductors. This phase has been prepared by sintering methods and shows usable amounts of ion conduction at room temperature in cells of the type $Mg|Ba_xMg_{6-x}Se_6|NbSe_2–I_2$.

Liquid Crystals

The investigation of the properties and uses of liquid crystalline materials has encountered an explosive revival during the last decade and particularly during the last five years because of their intriguing device applications and the ready availability of room temperature nematic liquid crystals (Schiff bases). Although cholesteric liquid crystals were first used in temperature-sensitive display devices, it is now apparent that the major device application of liquid crystals lies in the area of electrooptic display devices. The major advantage of these devices is their extremely small power requirements. Commercial numeric display devices are now appearing on the market in electronic watches and calculators and it is apparent that developments of new materials and device applications will continue at a rapid pace in the future.

One recurring problem is the need for more chemically-stable, room-temperature, liquid-crystal materials. Related to this problem is a better theoretical understanding of the forces contributing to liquid crystallinity, and the development of nonempirical approaches to the design of liquid crystalline materials having specific phase ranges. These problems are further related to the measurement and better understanding of the properties (thermodynamic and physical) of liquid crystals and the role of impurities in inducing changes in these properties (i.e. the mechanism of storage and the role of surface properties in inducing liquid crystal orientations). From a better understanding of liquid crystal properties, extensions might then be made toward the development of better models for the more disordered liquid state.

In recent years it has become apparent that lytropic liquid crystals may be important in biological processes. Certain viruses are known to possess the rod-like shape of liquid crystal molecules. In the future it will be of much interest to assess the influence of such materials on biological phenomena.

Biomaterials

A most promising growing area for materials research concerns the development of materials and devices for surgical and health use. At this interface between the inanimate and animate worlds answers to many intriguing questions will have to be found at a most basic level. Typical research topics in this area include:

(i) Surface Architecture—This also includes surface energy and changes which can occur as the result of contact with body fluids; for example, development of monolayers of lipids, proteins, etc.

(ii) Degradation—There is a need for further research on the mechanisms of degradation of polymers by water, lipids, proteins, and enzymes. This area also includes further work on the corrosion of metals and also the degradation of ceramic materials, frequently by hydrolysis. The converse area is also important; namely, passivation of metals to make them less susceptible to corrosion or the development of coatings to protect them. This can also apply to ceramics and polymers.

(iii) Bonding—The mechanism for the bonding by adhesives between metals or polymers and, for example, hydroxy apatite and collagen. This is important to both dental and orthopaedic needs; it is particularly a pertinent topic in dentistry where there is a great need for an adhesive between a restorative material and enamel to seal the margins.

(iv) Composite Materials—Especially development of a better understanding of the interface between the two components and the possible degradation of the interface. There are many common denominators between this problem and that already mentioned under (iii).

(v) Glass Ceramics—There is only a small amount of work being carried out on potential glass-ceramic materials based on the calcium phosphate glasses. These have potential for degradable devices in the orthopaedic field, among others.

(vi) Graphite and Carbons—Although there has already been much development of pyrolytic carbon for heart valves, more work needs to be done in the development of these materials which are well established as being compatible with the human body. Probably the major emphasis here, however, should be in the fabrication rather than the fundamental scientific aspects,

(vii) New Fabrication Techniques—Such as the freeze-drying technique for the fabrication of materials which have potential use for implants. Also, particularly intriguing is the replamineform process (replicated life forms or structures).

(viii) Membranes—A great deal still needs to be done on the development of membranes suitable for diffusion of gases (needed for devices for the measurement of oxygen, carbon dioxide, etc. as well as for long-term artificial lung devices). This is important in the area of in vivo physiological measurements on the body. There is still a great deal to be done in membranes for kidney dialysis. The big problem here, however, is cost since membranes currently exist which allow maintenance of life. However, as emphasis shifts towards full rehabilitation of patients there is a need for a totally implantable artificial kidney at acceptable cost and with superior performance.

(ix) Adsorption Kinetics—Reversible physico- or chemi-adsorption needs further development. This is particularly important in the coming area of drug release or its reverse, adsorption of toxic materials. Both polymer and ceramic or glass systems have potential in this area. The ultimate goal, for example, is to be able to “dial in” the release rate, particularly to develop a constant rate.

(x) Analytical Techniques—The application of current or new analytical techniques for studying change in tissue fluids or components; for example, changes in the conformation of polymers or proteins in the body such as hyaluronic acid, which is important in arthritis and is part of the synovial fluid in joints. Also, how these changes in conformation, etc., may change the calcium binding.

(xi) Biological Potentials—The effect of strain (or stress) on the development of biopotentials in natural tissue is still poorly understood. They are known to effect changes in the rate of dissolution or laying down of hard tissue, for example.

(xii) Reactions at Implant Sites—Blood clotting at implant sites is still an enormous problem. A major part of this problem revolves around the surface chemical architecture and the effect on protein adsorption. To date heparin-treated polymers with high surface energy have proved very successful as anticlotting material. In addition, there is a fluid mechanics problem associated with blood flow and surface adhesion and the interaction of the material in terms of fibrous ingrowth and calcification.

MATERIALS PROCESSING

Processing and Manufacturing Techniques for Metals

There are two main directions for innovation in processing: (1) attainment of microstructure not possible with conventional techniques, and (2) attainment of finished part more economically than otherwise. The latter includes finding ways to consolidate processing operations into fewer ones. In particular, all processing operations need to be viewed within the broad perspective of energy requirements. Although most innovative processing techniques are primarily developed for specific materials and applications, basic research in this area should spawn new approaches. Examples from four major categories of processing are illustrated below. In addition, two research topics relevant to processing (metastable phases and computer simulation) are discussed.

Extractive and Process Metallurgy

The need for new and improved beneficiation and extractive metallurgy processes is widely recognized and has acquired a certain sense of urgency in light of mineral demand trends, decreasing ore quality, increasing energy costs and environmental constraints. Many of these needed advances will come from process improvements that retain the basic chemistry and basic design of an existing process and, as such, fall within the realm of engineering development. Additional advances will come from new processes which retain the same basic chemistry but invoke new or novel concepts of momentum, heat, or mass transfer or of fluid flow. The final category, and that of most interest here, relates to new processes involving novel chemistry.

In the area of ore or mineral beneficiation research is required to more fully understand the properties of interphase and grain boundaries so that mineral aggregates can be efficiently and preferentially separated at these boundaries. Further research is also required on the fracture and flow characteristics of mineral phases as a function of temperature, and perhaps in the presence of surface active agents, in support of improved, preferential separation techniques. A second, broad research area in ore beneficiation, involves the handling and efficient separation of fine particles (<20–30μm) produced from prior comminution. Ultraflotation techniques, selective agglomeration, electro-phoretic methods, and the utilization of ultrahigh magnetic or electrostatic fields are only some of the techniques which may lead to new and useful technologies for the efficient recovery and separation of fine particles. A corollary here is that of tailor-making chemical reagents for flotation and solvent extraction use. Improved knowledge of the properties of mineral-solution interfaces and the relationship between the structure of flotation reagents, mineral crystal structure and flotation and extraction behavior is essential for making significant advances in these areas. Research on wholly dry separation techniques based on the gravitational, electrostatic and magnetic properties of particles should not be ignored since these will be particularly relevant to beneficiation in arid regions.

New processes which retain the same basic chemistry but invoke new or novel process concepts, i.e. the interaction of this basic chemistry with the physical phenomena of momentum, heat and mass transfer, offer challenging research opportunities. There is, for example, the continuing need for modeling flow and transport behavior in heterogeneous systems which are those most often encountered in real processing. Some of the newer computer simulation methods for use here are described elsewhere. The coupling and refining of such modeling with innovative techniques of experimental process analysis is also a legitimate and much-needed research activity. The success of an analytical method or model depends much less on the amount of theory which it incorporates than on its reliability as a mirror of reality—and that reality is provided by experimental process analysis. It must be noted that much of our current materials processing, particularly process metallurgy, suffers from a lack of real-time data acquisition and feedback control and that such control will be a necessary feature of new processes to optimally exploit the research results derived from the modeling and experimental process analysis indicated.

The discovery of new processes involving novel chemistry provides a wide-ranging field of research. Much of this “novel chemistry” may already exist in the immense chemical and metallurgical literature although additional research will be needed to amplify and extend our understanding of promising systems. However, significant areas of novel chemistry remain to be explored. These include aqueous chemistry at elevated temperatures and pressure, vapor— phase chemistry, fused salt and nonaqueous solvent chemistry, electrochemical methods in aqueous and nonaqueous systems, ion exchange and solvent extraction. The use of novel reductants such as solvated electrons and atomic hydrogen may offer new and interesting possibilities.

The possibilities of novel chemistry in pyrometallurgical processes should not be ignored either, even though our knowledge here is fairly extensive. Careful control of thermodynamic and kinetic conditions may offer new extractive possibilities not previously thought feasible. Novel chemistry involving metastable phases should be considered. The pyrometallurgy of oxide, sulfide and metal phases will remain a major process for the production of large-tonnage metals and, as such, warrants our continuing close attention.

Casting

Melt spinning—This relatively new technique of casting metal filaments by extruding a liquid jet through a fine orifice may lead to high-speed production of fine wires in a single step. The challenges in this area include hydrodynamics of the liquid jet, chemistry of surface films developed to stabilize the jet, and casting defects, solid state reactions and resultant properties associated with high cooling rates.

Rheocasting—Another new technique, involving material cast in the partially-solidified state. High fluidity is maintained by vigorous mechanical stirring. Because of lower pouring temperature, there is less mold erosion, centerline shrinkage and freezing time. If the stirring is momentarily stopped, the slurry stiffens and can be handled like a solid for die casting (thixocasting). Or, particulate materials can be added and uniformly blended in composite fabrication (compocasting). Two notable areas calling for study are: (1) fluid flow and rheology of partially-solidified alloys, in particular as to the size, shape and distribution of the solidified portions, and (2) microstructure (e.g. microporosity, dendrite structure) and properties resulting from this type of casting. New alloys may have to be designed to realize the full potential of rheocasting.

Melt Saturation—A technique for preparing dispersion hardened alloys by mixing two or more molten alloys, e.g. Cu-Th and Cu-B to obtain ThB dispersion strengthened Cu, taking advantage of a single step of dispersoid formation and of the faster reaction kinetics at elevated temperatures. Studies of reaction kinetics and fluid flow of mixed molten alloy systems and resultant structure and properties are needed, perhaps in combination with rheocasting.

Other areas to be exploited include continuous casting, ferrous die casting, electroslag remelting, and directional solidification.

Working

Thermomechanical Processing—Properties of practically all commercial alloys as well as new alloys can be optimized by controlling the thermal and mechanical cycles of processing. Severe cold working of several nominally single-phase Cu alloys followed by moderate temperature annealing, for example, results in enhanced strength for given ductility. The enhancement comes from a superposition of texture sharpening, increased dislocation density and deformation-enhanced precipitation not achieved with small degrees of prior deformation. As another example, the development of stable elongated grain structure in dispersion strengthened Ni and Al alloys by TMP, has resulted in a considerable improvement in high temperature creep strength. Future advances will come from a reexamination of the complex interaction of deformation, recrystallization, texture development and solid-state reactions in the important commercial alloys. For selected applications where deformation is not possible, shock by explosives, pulsed lasers, gas guns, etc. may be used for textured metal formation.

Powder Metallurgy—Two areas for research are: (1) Novel means of preparing powders of controlled size, shape, composition and structure with a view toward optimizing the properties of the finished parts. Examples of such processes include splat cooling, electric spark discharge, cold substrate deposition, freeze drying and various redox reactions. New directions for such materials include acicular Co-Fe magnet powders for enhanced shape anisotropy, and amorphous powders for enhanced chemical reactivity. (2) Thermal and mechanical behavior of powder preforms with a view to optimizing properties via thermomechanical processing (e.g. improved density and texture development via hot working of preform). Advances in this area could lead to economical production of specially-designed alloys or composite structures.

Hydrostatic Pressure Forming—In addition to continuing development of the engineering aspects such as those providing for continuous operation, there is need for extensive study of the effects of temperature and reactivity of the pressurizing fluid with the alloy (e.g. protective coatings). In addition, studies are required of the structure and properties of parts formed under hydrostatic pressure to insure optimum alloy design from the fabrication standpoint and to extend this technique to the forming of wider range of materials. Volume changes in plastic deformation, such as may be manifested in S-D (strength-differential) effects, should be examined critically both microstructurally and in terms of plasticity theory.

Superplastic Forming—Structural requirements such as fine grain size are fairly well characterized. Future efforts will likely be on novel techniques for achieving the required microstructure (e.g. powder metallurgy for fine grain size), particularly in normally hard-to-form materials (e.g. ceramics and refractory alloys) where superplastic forming may be of added advantage. Problems of die material for high temperature operation need to be met, and ways may need to be developed to alter the microstructure to inhibit superplastic flow during service.

Joining and Finishing

In joining techniques such as diffusion bonding used in fabricating metal matrix composite materials, basic studies of adhesion as influenced by solid state reactions in the presence of heat and pressure, surface films, etc. are important. For the newer welding techniques such as those using plasma arcs and electron and laser beams, structural changes and resultant properties in the weld region need to be studied. Similarly, structural and compositional changes resulting from finishing operations, such as electric discharge machining, electrochemical machining, and laser machining need to be determined more thoroughly. New approaches to coating, such as flame spraying, again require studies of resultant microstructures and properties. Particularly important is research aimed at developing metals with a built-in ability to generate protective coatings during service, such as by the incorporation of Al and Cr to TD nickel to provide outstanding oxidation resistance without external coating. The role of dispersed oxides and rare earth additions (e.g. Y) in improving adherence of scale in coatings also needs clarification.

Metastable Phases

Nucleation and growth transformations require time for the process to start, and to continue. Thus, if insufficient time is allowed for atomic diffusion, then transformations can be suppressed and those which do occur are kinetically fastest; generally producing metastable phases. This kinetic effect has been exploited by the “splat cooling” technique in which molten alloys are shot on to a cold substrate. Splat cooling is the fastest quench obtainable-for quenching materials directly from the liquid state, and quenches of from 10^7 to 10^9ºC/sec have been achieved. Splat cooling has produced many new materials; metastable solid solutions (in which precipitation has been suppressed), metastable crystal structures (even simple dubic), and the first metallic glasses, in which crystallization itself is by-passed. Many of these metastable phases have novel and useful properties—e.g. 1) the superconducting compound Nb_3Ge forms a metastable material whose transition temperature is 17ºK, an increase of 10ºK over that of the equilibrium, not splat-cooled, form; 2) new semiconducting materials such as crystalline metastable solid solutions in the system Ge-Ga-Sb, and glassy tellurium-based alloys; 3) magnetic alloys with increased coercive force; 4) splat-cooled metallic glass alloys that are among the mechanically strongest of the nonferrous materials; and 5) ferromagnetic metallic glasses in the systems Pd-Co-Si, Pd-Fe-Si, and Fe-P-C. The alloy $Pd_{.68}Co_{.12}Si_{.20}$ has an unexpectedly high coercive force of 160 Oe, whereas Fe-P-C alloys have the low coercive force expected for disordered, amorphous structures.

Clearly, the ability to produce metastable states has opened up vast possibilities for the preparation of new materials. Past research has concentrated on structure; demonstrating the amorphous nature of the metallic glasses, for example. There is presently, however, a change in emphasis to that of using splat-cooling to enhance, or originate, specific properties. Many questions need to be answered—for example, what are the mechanical, corrosion, and transport properties of a material, such as a metallic glass, which has no grain boundaries or other imperfections. To utilize the technology important properties of splat-cooled materials, methods of fabrication into usable forms must also be devised.

Computer Techniques in Processing

The ability to predict macro-phenomena of a material based on microtheories under the complex conditions of processing is essential to the understanding and development of new and efficient processing techniques. In this regard modern computer simulation of material behavior in continuum physics is indispensible. Two complementary computer methods have been developed.

The finite element methods are most suitable for small displacements. Applications have included three-dimensional stress analysis, viscoplasticity, heat transfer, fluid dynamics, electrodynamics and electromagnetics. It should be possible to extend these techniques to analyses of deformation of composites, thixocasting, injection molding, nucleation mechanisms in crystal growth, and the terminal phases of processes such as dynamic super-plasticity and splat cooling.

In contrast to the finite-element methods, the particle-in-cell techniques show their forte in modeling large and complex material displacements and various mixing or transport mechanisms, including turbulent flow fields. These methods could thus simulate not extrusion, the initial high-velocity phases of dynamic, superplastic forming or splat cooling, and the convection and diffusion processes surrounding crystal growth.

As part of a systematic exploitation of these computer methods, a significant effort needs to be directed toward having the two methodologies complement each other for the most effective and computationally-efficient approach to specific problems. The stakes in terms of programming effort and machine time can be high.

Rubber and Plastics

The processing of conventional rubbers is quite a costly step in manufacture. Many possible ways of reducing or eliminating certain steps have been investigated. As an example of current interest some rubbers are now marketed in powder form so that the initial mixing may be carried out by blending. This blending to form a mixed powder could then be followed by direct feeding to extruder or injection molding press.

Another more attractive possibility involves mixing of a low molecular weight rubber as a liquid. This would avoid the power-consuming shearing action necessary with solid rubbers. The low molecular weight rubber would, after mixing, be chain extended and then crosslinked, ideally in a single step, to give a product equal in properties to that obtained by present day processes. To achieve this end a number of advances are necessary. The action of reinforcing fillers is often found to be dependent upon high shear mixing. Understanding of this process would hopefully lead to the development of methods making this unnecessary. A range of elastomers with chemical reactivity appropriate for the chain extension and crosslinking together with the corresponding linking agents are required. Some of these difficulties have already been overcome in polyurethane systems giving hope of further extension into other rubbers.

An area that is exciting interest concerns the cold forming of both amorphous and crystalline polymers, a method that avoids the energy and time required to heat a polymer above its softening point or melting point and then cool it down again to room temperature. Injection molding of thermoset resins also looks promising—cycle times for heavy section moldings are currently faster than with injection molding.

Perhaps one of the most urgent technical problems in the plastics processing field is to find efficient methods of recycling. Recycled polymers continue to expand in both variety and volume of production. Reclamation of rubbers by mastication and of monomer from poly (methyl methacrylate) by pyrolysis are now well established processes. Likewise, much newsprint is now recycled, and a method has also been developed for recovering poly (ethylene terephthalate) from textile mill tailings and photographic film. Perhaps effort has tended to be more concentrated on recovery rather than recycling, and there is need for developing ways to use scrap as a raw material for new processes. Thus, used automobile tires may be used as a source of chemicals (by destructive distillation) or carbon black (by controlled combustion). The established reclaiming process to reform a rubber is more complex and yields a material which might be more accurately classified as a compounding ingredient rather than a raw rubber. A process which competes with recycling polymers is to use them as fuels—for example, tires yield 50 percent more heat than coal—but a most pressing need is to find effective recycling processes for polymers which give unpleasant or poisonous fumes on burning. Polyvinyl chloride is perhaps the most important such polymer because of its large production, but there are many others. It yields hydrochloric acid on burning which must be removed and prefarably used before discharge of the combustion gases.

Techniques involving biodegradation are poorly developed. So far in many cases they may lead to useful products and as a minimum lead to non-dangerous and easily disposable materials. In all considerations of recycling it must be remembered, however, that we have a people problem and an economic problem. Most of the processes require a substantial supply of clean material (scrap). Factory scrap is the first choice; but to really operate efficiently, provision must be made for adequate separation of refuse with economic transportation to recycling plants. The creation of such a system is perhaps not the province of the scientist but is essential to the application of science to recycling.

Electronic Materials

Single crystals are the cornerstones of solid state electronics. As in the past, future innovation in electronic materials will depend heavily on furthering the art and science of crystal growth. The search for new crystals with novel properties often occurs beyond the reaches of the predictive power of physical theory and has to rely heavily on intuitive interpolation and extrapolation of trends in the periodic table, atom sizes, crystal structures, bond polarizabilities, etc. The electronic materials of the future will be more difficult to prepare and the quality and perfection requirements will be more stringent. Higher melting points, higher volatilities, ternary and quaternary compounds, pose greater problems than did the elemental semiconductors, germanium and silicon. Yet even with silicon the demands of modern integrated circuit technology make it necessary to find ways to achieve even greater control over the presence of impurities and imperfections than is presently typical.

Effective search, strategies for new electronic materials call for close liaison, often on a day-to-day basis, between those engaged in the chemical and metallurgical aspects of crystal growth, and those primarily concerned with their physical properties. More complete knowledge of each other's area of expertise can only help the synergistic process.

A wide range of crystal growth and preparation techniques is now available: pulling from the melt, hydrothermal growth from hot aqueous solutions, flux growth from other solutions, growth directly from the melt, epitaxial methods for thin films, chemical vapor deposition, ion implantation, etc. Each method offers advantages and disadvantages for a given material, but in all cases the trend is toward greater control over the resulting crystal composition, purity, and homogeneity. More complete understanding of crystal growth processes and the factors affecting them, such as convection instabilities in the liquid phase, and more detailed knowledge of the factors determining phase diagrams and which impurities, if any, can be used to dope crystals p- or n-type are needed. Theoretical crystal growth studies at the atomic level, particularly by computer modeling, together with careful experimental studies of growth and initial nucleation on clean surfaces using, for example, molecular beams, are advancing to the point where theory and practice should begin to mesh.

Control of the nature, density and distribution of point, line and planar defects in single crystals is essential in the interpretation and control of structure sensitive properties. For example, isolated or clustered vacancies, interstitials and impurity atoms, second phase particles, dislocations and dislocation arrays, stacking faults, antiphase boundaries and magnetic domains can be present in the as-grown condition or form after growth as a consequence of imposed conditions. The control of these defects requires, firstly, their detection and characterization and, secondly, knowledge of how the defect state varies with imposed conditions (e.g. heat treatment, impurity doping, thermal-mechanical treatment, irradiation, oxidation, electrical or magnetic fields, etc.). Given these factors it is, in principle, possible to manipulate crystal growth variables so as to produce a particular as-grown defect structure (e.g. dislocation "free" silicon) and to utilize as well as operate within the boundaries of imposed conditions so as to both design a particular defect structure and maintain or minimize changes in desirable defect structures.

To a large extent the detection and detailed characterization of lattice defects is now possible because of continual development of sophisticated X-ray and electron optical instrumentation over the past twelve years and simultaneously because of major advancements in the theories of diffraction and image formation. Using X-ray diffraction and topography techniques defects present at the micron scale can be studied whereas defects present on the near atomic scale can now be studied with electron optical equipment which combines high, resolution electron diffraction and microscopy with energy analysis and selection techniques. Most studies, however, have been concerned with, surveys of defects in as-grown, quenched, irradiated or mechanically-damaged metals, metal alloys and, to a lesser extent, oxides (i.e. structural materials). The knowledge derived from these studies has been used primarily to better our understanding of the fundamentals of deformation and fracture processes. Similar attention has not been given materials whose electrical, superconducting, magnetic and optical properties are of principal importance. This neglect has produced a significant knowledge gap in design, fabrication and quality control areas where these materials are utilized.

Nowhere in electronic materials are such exacting demands made on crystal quality and defect control as in integrated circuit technology. At the same time, the trend has been to even greater extremes of miniaturization. But in one respect, electronics has remained unaltered over the years. Components both active and passive have been interconnected according to the precepts of classical circuit theory. What has changed, and changed remarkably, is our ability to fabricate smaller components and make the interconnections at progressively lower cost and higher reliability. The cost of a transistor in complex circuits has decreased some ten thousand fold since 1960, and yet the reliability of large scale integrated arrays containing thousands of components approaches that of single discrete components. Concurrently with the increasing scale of integration on monolithic silicon devices, the need in analog circuits for precision resistors and capacitors has led to the development of these components in precision thin film form. When interconnected on a common substrate with silicon devices, a powerful and adaptive hybrid integrated circuit technology results.

The development of large scale silicon monolithic integrated circuits for both the bipolar and metal-oxide-semiconductor functions has been made possible mainly by evolutionary improvements in materials and processes which have steadily reduced the numbers of defects introduced at each stage in the complex processing sequence, by defects which can cause a device malfunction. Defects can enter a device in three ways: intrinsic defects in the starting materials; processing defects where a process step fails locally to generate the required structure; and defects due to the photolithography process or the photomasks themselves.

At present, the last two categories are the most critical. Many of the processing steps used in fabricating integrated circuits are less than perfectly understood, and would benefit substantially from basic study. Examples are the structure sensitivity of electrical properties in SiO_2; factors affecting the surface state density and charge mobility at Si/SiO_2; interfaces; the thermodynamics and kinetics of the formation of ohmic contracts between metals and silicon.

The photolithographic process and particularly our ability to make defect-free masks is now one of the most crucial obstacles to further increase in the scale of integration. Radical new approaches are needed here since detail on current silicon integrated circuits is delineated to limits too close to the optical diffraction limit, and further substantial improvement in the process is impossible. In view of this, many of the major semiconductor concerns are now developing electron beam lithographic processes for direct lithography on silicon. Crucial to this effort is the synthesis of new polymeric electron resists and improvements in our understanding of the physical processes occuring during the interaction between electron beams and these polymer films. The substantial impetus behind electron lithography is the factor of 10^2–10^3 increase in packing density over the present state of the art which the technique ultimately offers, with its attendant large reduction in cost. But once this is attained, the fundamental size limitation on both bipolar and metal oxide semiconductor (MOS) devices will have been reached.

Further progress at this point will be possible only by reducing the total number of components in a system. To do this, our old approach of reproducing physically the elegance of classical circuit mathematics will have to be abandoned in favor of functional electronics—where basic properties of matter are used directly to perform circuit functions.

One of the oldest and best examples of a functional device is the piezoelectric quartz crystal resonator. Nowhere within the quartz can the inductive or capacitive components of its classical circuit analog be isolated. Other examples are quartz and glass delay lines, Gunn effect and Impatt oscillators and amplifiers, acoustic wave transducers, elastic wave amplifiers made from piezoelectric semiconductors, magnetic bubbles, acoustooptic and electro-optic modulators. The latter two are particularly interesting in view of the prospects for early use of optical communications systems. The hybrid approach to integrated electronics offers an easy vehicle for the introducing and interfacing of optical devices with other more conventional electronic elements. Major opportunities for long term materials research lie in this field of functional electronics.

Instrumentation, Analysis and Testing

The practice of testing and delineating the characteristics of materials, especially those related to performance, runs through all technology. Testing is required for quality control; for establishing standards to ensure in-service durability, reliability, and safety; for sensing in production processes and automation; and to avoid environmental degradation.

In a 1967 report, Characterization of Materials,* the Materials Advisory Board stated, “Attempts to provide the superior materials that are critically needed in defense and industry are usually empirical and often wasteful of efforts and funds. That is so, chiefly because we do not yet have a fully developed science of materials that affords predictable and reliable results in devising and engineering new materials for specific tasks.” A definition was proposed—“Characterization describes those features of the composition and structure (including defects) of a material that are significant for a particular preparation, study of properties, or use, and suffice for the reproduction of the material.”

Destructive or nondestructive tests are required to determine the many characteristics of materials; mechanical, electrical, optical, and other physical properties; composition and structure; defects and impurities. Understanding of the relationships between properties and performance, of the mechanisms of degradation and failure, and of the interaction of matter with

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*Publication MAB-229-M, National Academy of Sciences-National Academy of Engineering, Washington, D.C., 1967.

various forms of radiation is essential to the development of testing methods and equipment. The latter, in addition, must be designed to function in the pertinent service environment.

Technology and basic research interact strongly in the development of instrumentation. The initial models of many sophisticated instruments are built, as a rule, for specific research projects. Often this instrumentation eventually becomes standard for production or quality control. One example is the thermocouple, which resulted from basic research in the 19th century on the thermoelectric effect. The thermoelectric properties of many materials were determined, and this led to the adaptation of the phenomenon to measure temperature. Other well-known examples are X-ray diffraction, the optical and electron microscopes, and spectrochemical analysis.

The realization that the composition of the surface of a solid usually cannot be inferred from measurements of the bulk material has stimulated the development of new spectrometric instruments for surface analysis. Much of the current effort is aimed at establishing the full potential of these tools, which include the ion probe, the X-ray photoelectron spectrometer, the Auger spectrometer, and the ion-scattering spectrometer.

Analysis of ultrapure materials is seriously challenging analysts. Improvements are required in the mass spectroscopy of solids and in activation analysis. Ecological concerns are largely responsible for an upsurge of interest in the detection of organic compounds, such as those present in trace amounts in biological materials. Advances will be sought, as a result, in mass spectroscopy, infrared techniques, gas chromatography, electrophoresis, and other analytical methods.

Nondestructive testing is among the areas of materials technology requiring urgent attention. In the past, nondestructive testing generally meant testing only for geometric size, defects, and some mechanical properties, but it should be interpreted much more broadly—testing for composition, microstructure, and the full range of physical properties. Basic research in solid-state physics and chemistry, aimed at detecting and understanding certain properties of materials, has spawned many of the modern techniques for nondestructive testing. The methods depend heavily on the interaction of matter with optical, electromagnetic, acoustical, and other forms of radiation. A few examples of techniques of current value or being developed for nondestructive testing are: electron paramagnetic resonance (fracture of polymeric solids, stress analysis); nuclear magnetic resonance (chemical analysis; Mössbauer spectroscopy (surface-chemical and phase analysis, stress analysis); optical correlation (surface distortion); infrared spectroscopy (thermal analysis, flaw detection); microwave attenuation (moisture content); optical and acoustical holography (stress analysis, flaw detection); acoustic emission (flaw detection).

Routine use of these methods in nondestructive testing, however, requires more understanding of the physics of the phenomena involved, its quantitative relationship to the physical property to be monitored, and the limits of applicability. Required also is instrumentation that offers improved signal detection and reliability as well as greater physical ruggedness and ease of testing, especially in portability and automatic readout of easily interpretable data.

BASIC RELEVANT PROPERTIES OF MATERIALS

Superconductivity

One of the most tantalizing challenges to materials scientists is that of finding practical superconductors with, higher transition temperatures than those currently known. There is great potential technological value of high temperature superconductors for electric power generation, transmission, and novel modes of high-speed ground transportation. Hundreds of elemental and compound superconductors have been discovered or synthesized and transition temperatures as high as about 23.2ºK. have been achieved but the advance is slow—only about 5ºK over the last decade despite much effort and many materials preparations. On the theoretical side developments in 1957 (the BCS theory) did much to clarify the mechanism of superconductivity and rationalize various experimental observations. There remain unanswered questions regarding the fundamental limitations which the lattice and electronic structure of real solids impose on the transition temperature. Until recently much of the search, for higher temperature superconductors concentrated on trying to find the “magic” electronic structure. Recently it has become more apparent that the dynamic properties of the lattice (phonons) are at least as important; in particular, lattices which undergo structural transformations accompanied by, or triggered by, certain of the lattice vibrations going to very low frequency (soft modes) have been found to be particularly prone to be high temperature superconductors. To put these results and ensuing phenomenological models on a rigorous and quantitative basis is a particularly exciting and urgent challenge to materials science. In the meantime, intriguing progress is being made by focussing the search on materials with relatively unstable or metastable lattices, either as a basic property or as an artefact attained by some preparative technique such as rapid quenching.

Extensions of Laser Action

Though lasers are by now well known and understood and new applications for them are steadily being found there are three areas where orders-of-magnitude improvement are needed—higher power, shorter pulses, and shorter wavelength.

The power limitations for solid lasers are not yet known nor is much understood about the limiting mechanisms of optical breakdown. Recent development of ultraviolet-assisted large volume CO_2 gas lasers appears to have opened a new era in the direction of rugged, inexpensive, ultrahigh power sources. There is hope that the same principles can be applied to shorter wavelength lasers such as the 3371Å N_2 laser or even the recent H_2 laser which has operated down to 1161Å. With such actual and anticipated developments comes the need for solid materials for optical elements: windows, mirrors, lenses and nonlinear optical elements. The anticipated use of high power lasers for nuclear fusion initiation will likewise provide tough challenges to materials science.

The production and control of short ($\lesssim 10^{-12}$ sec) optical pulses calls for a more thorough understanding of the very short time dynamics of materials. The recently-developed optically activated Kerr-type shutter whose response is limited by the molecular reorientation time of a liquid molecule is an example. As times become shorter and laser pulses more intense, much of our physical understanding of materials which is largely based on thermal equilibrium states will prove inadequate.

The achievement of shorter wavelength laser sources—ultimately into the X-ray region—is an extremely important goal. Attempts to use solids with larger bandgaps would suggest the rare gas solids (and possibly liquids) as fertile fields of research. The possibility of pyramiding nonlinear optical processes up to the 15th or higher harmonics of the fundamental is already under serious considerations, using phase matchable metal vapors as the nonlinear material. Much more effort is called for on direct soft X-ray lasers, probably using low-lying nuclear energy levels. This is an area where a novel approach is most likely required.

The potential benefit to materials science and engineering from such research is obvious in several ways: X-ray holography, direct measurement of bond charge distributions, and inelastic scattering from excitations of even the smallest wavelength would revolutionize our methods of studying and characterizing materials.

Continuously tunable laser sources are now a reality in several embodiments: dye lasers, magnetic spin-flip Raman lasers, pressure-tuned direct gap semiconductor lasers and parametric oscillators. Without exception these devices are based on basic research of a decade or more previous. The tuning, modulation and control of the higher power, short pulse, short wavelength lasers of the future will undoubtedly make use of the interaction of the laser energy levels with external perturbations, in markedly nonequilibrium conditions.

Present research in materials science is developing knowledge concerning the interaction of lasers with materials. Areas such as laser-induced shock strengthening of metal surfaces, laser welding, and machining of ceramics and metals with lasers will benefit from such materials research.

Fracture Toughness

The importance of a fundamental understanding of fracture toughness to the design of safer and more reliable engineering structures is obvious. But as in so many other areas of materials science and engineering our present understanding at the atomic level is not sufficient to provide a reliable predictive capability. Instead, the most fruitful approach has been in the area of fracture mechanics. Most research to date has revolved around continuum models of crack propagation, particularly concerning energy release criteria and stress intensity factors for crack propagation. More recently somewhat more sophisticated theories of fracture which take into account polycrystallinity, or microstructure, have resulted in improved understanding, better testing procedures, and the development of tough materials. As the ignorance factor is diminished so there can be significant materials savings by minimizing the need for over-design. But much, more needs to be done. Improved models are needed to close the gap between continuum and microstructural theories of fracture by taking into account the nature of the polycrystallinity, anisotropy, and time-dependent material behavior. More understanding is needed of the dynamics of crack propagation and the effects of the statistical nature of the microstructural elements. Here, innovative use of computer modelling techniques can be expected to play an important role. But ultimately we need to know more about fracture initiation with regard to actual breaking strengths of metallic or chemical bonds, the role of lattice vibrations in a distorted or defect-riddled lattice and, potentially pertinent to the severe technological problem of stress-corrosion cracking, the dynamics of the chemical reactivity of stretched or otherwise distorted lattice structures and individual interatomic bonds.

Dynamic Behavior of Defects

When dislocations first were directly observed by transmission electron microscopy in the mid 1950's, great impetus was given to both experimental and theoretical study of dislocations in both single crystals and polycrystalline materials of commercial interest. As a result, the treatment of plastic deformation of crystalline materials by dislocation motion and interactions has been greatly facilitated. Modern research and development of structural materials is now related to the concepts and methodology of the dislocation treatment. There is still a great deal of basic work left to do in advancing the dislocation theory and its application to structural materials development. A current thrust in research on dislocations includes the combination of dislocation theory with continuum mechanics, resulting in a continuum theory of dislocations. Work is needed particularly on the transition from dislocation behavior to continuum behavior under dynamic conditions. Another area of research is the use of computers to average individual dislocation reactions into a net plastic deformation. Still a third area involves dislocation dynamics under high strain rate conditions, such as those prevailing in the vicinity of an advancing crack and those inherent in shock deformation and laser pulsing.

The field is at the stage where applications of the theory are being made through analytical models relating the dynamic behavior of dislocations and point defects to mechanical behavior; e.g., such practical applications as creep and hot pressing of crystalline solids. This is accomplished by computer "mapping", whereby various theoretical constitutive equations are used to predict in stress-temperature space, regions where specific mechanisms of high temperature mechanical behavior are operative.

The effects of point defects in the mechanical behavior of materials are of particular importance at high temperatures, where redistribution of point defects and dislocations may occur. Effects on high temperature strength performance are related to vacancy transport (diffusion) and the formation of stable dislocation substracture and dislocation networks. Of particular importance is the combination of high temperature and neutron flax, such as that prevailing in a fast breeder nuclear reactor. Here the dynamics of vacancy agglomeration into voids poses a severe challenge, as well as the broader area of gas (hydrogen and helium) generation and agglomeration.

Our ability to treat the dynamics of surfaces or interfaces at elevated temperature rests on our ability to treat dynamics of point defects (interstitials and vacancies) and line defects (dislocations). These are inextricably related to the structure of area defects (surfaces and interfaces). There is little doubt but what high temperature structural strength is directly related to the stability of the three-dimensional network of area type defects, which can be facilitated by solute and particle pinning.

Flammability of Polymers

Flammability, an especially fast form of surface chemical reaction, is of particular concern in the use of polymers. There is need for better quantitative determination of the important variables of burning. For example, counterparts to the oxygen index test, used for rating precisely the ease of burning of individual materials, have to be developed for entire materials systems or products under conditions reflecting their performance in end-use environments.

The high-temperature, free radical reactions of polymer combustion, encompassing oxidation and pyrolysis in both the flame and degrading polymer, are now understood in only qualitative terms. The interaction and sequence of the important physical and chemical processes, and how they may be slowed or altered by the addition of various fire retardants, represent a challenge to modern research very similar to that posed by catalysis.

In a second category, the results of practical efforts to devise significantly better fire retardants for flammable materials have apparently peaked. Little real progress has been made other than to optimize the form and amounts of antimony, halogen, and/or phosphorus in a particular material or application. Furthermore such treatments are now known to increase greatly smoke and toxic gas formation. Although synthesis of inherently nonflammable polymers has given us materials such as the polyimides, they have not so far been economically feasible except in limited use applications.

The most promising improvements will probably come from careful design and engineering to give system-wide rather than mere individual material protection. The age-old, reliable sprinkler system is a trivial example. The recently-reported experiment of protecting the inside of an entire aircraft fuselage for over ten minutes in a raging inferno of burning fuel solely with intumescent insulation is an excellent instance of innovation in this area.

Photochemistry

Chemical changes resulting from exposure of materials to light can be deleterious or useful. Sunlight can cause plastics (such as automobile upholstery) to discolor, decompose and crack. On the other hand, photochemical reactions are the basis of photography. Related photochromic effects offer promise for information storage and holography.

The renaissance of organic photochemistry began only a decade ago. Many basic principles and reactions were discovered but a deeper understanding of reaction mechanisms is still necessary not only if photo-induced material degradation is to be avoided, but if the full synthetic utility of photochemical processes is to be realized. There is considerable promise for those reactions, which frequently occur under mild conditions, in the synthesis of chemically-sensitive species of pharmaceutical and biological interests.

There is still much improvement possible in silver halide photography and the development of grainless nonsilver imaging systems is still in its infancy. The related areas of high density information storage with photochromic or holographic techniques requires more fundamental investigation of photochromic compounds and photopolymerization. Photo-induced changes in the electronic configurations of certain dye molecules have led to tunable dye lasers. Further research on the electronic configurations and properties of organic molecules may be expected to yield both important scientific information and practical benefits.

Corrosion Resistance

Although much progress has been made in understanding the thermodynamics and kinetics of the corrosion process, the mechanisms of localized corrosion and the mechanisms for imparting corrosion resistance or protection against aqueous or gaseous corrosion are not well understood.

For localized corrosion, e.g., pitting and stress corrosion, initiation is distinct from propagation. Initiation may involve the breakdown of a surface film; important factors to be studied are variations in film composition and microstructure down to the atomic level and their interaction with the environment. Initiation can also occur at surface inhomogeneities; the types have not been clearly characterized. The propagation of stress-corrosion, hydrogen-embrittlement, and corrosion-fatigue cracks is not understood. As the use of high strength materials increases, these problems become more important; for example, susceptibility to hydrogen embrittlement increases with the strength of the steel. The mechanism of stress corrosion is probably different for each system. Problems pertinent to numerous systems include (1) the role of mechanical fracture, (2) the effect of stress on the rate of anodic dissolution, (3) continuous vs. discontinuous cracking, (4) the relevancy of continuum mechanics, as opposed to atomistic analyses of crack propagation, (5) the effect of defect structure and of chemical composition and distribution at the macro and micro levels in the metal, (6) the role of hydrogen generated at the crack tip. A high hydrogen fugacity in the vicinity of the crack tip is not a prerequisite for hydrogen embrittlement. However, it is not clear which of numerous other proposed mechanisms, if any, explains this phenomenon satisfactorily.

The corrosion of alloys by gaseous environments can cause surface roughening, most likely due to the preferential attack of the less noble constituent, and can result in a poor surface finish and in poor adhesion of surface films. The theory of surface instability and the mechanism of surface roughening are poorly understood.

High technology industries operate under unexplored conditions. Research is required for corrosion in aqueous media at high temperatures and/or pressures and in the ocean near the surface and at great depth, in highly corrosive body fluids for prostheses, and in gaseous media for thin metal films, the properties of which may differ radically from the bulk ones.

Research in the protection of metals falls into two classes: alloy composition and protective coatings. Although the specifics may vary, the basic questions to be answered are similar for most corrosion systems, including most alloys, aqueous and gaseous environments, and temperatures from below 273 K to above those at which the superalloys can be used economically at the present.

Small changes in chemical composition can radically change an alloy’s corrosion resistance, due to an intrinsic change in the alloy or due to composition changes in surface films. Research must determine the properties imparted by and the role of the alloying addition as affected by its presence in solid solution, in microsegregates, and in second phase particles. Research must also determine the effect of alloy composition on film composition and microstructure and then relate these to the problems of the transition from internal to external oxidation, the adhesion and the spalling or corrosion films, the resistance to breakdown of these films, and the mechanism of self healing. More specifically, the following must be studied: the crystallography of the films and the factors that determine crystal size and transitions between the crystalline and amorphous states; the defect structure, the conductivity of and diffusivities within the films and their effect on film growth kinetics; the mechanical properties of corrosion films; the thermodynamics and kinetics of the transformation from one corrosion product to another during high temperature gaseous corrosion of complex alloys. The above studies should lead to new alloys with better corrosion properties or to cheaper alloys.

Protective coatings fall into two classes: inhibitors are of monomolecular dimension and reduce the anodic or cathodic reaction rate, whereas thicker films provide a physical barrier. The interaction of inorganic inhibitors, e.g., chromates, with a metal surface is not understood. Are they adsorbed? Are electrons transferred, i.e., is the metal oxidized? Are all surface sites equally affected? The application of metallic coatings can result in the formation of intermetallics at the interface between the metals. Their role in adhesion and in corrosion protection is not always understood. The possibility of using metals that form corrosion-resistant oxides, e.g., chromium or aluminum, as coatings on the refractory metals for high temperature (> 1400 K) applications should be studied along with the resulting chemical and metallurgical problems. For organic films basic research is needed on the mechanism of adhesion.

BASIC GENERAL PROPERTIES OF MATERIALS

Interatomic Forces, Chemical Bonding, and Lattice Stability

There is no more Basic property of a material than that it exists. Yet, despite the enormous advances in solid state theory we are not able to predict from first principles and the appropriate atomic wavefunctions the configuration and dimensions of any crystal lattice except for a handful of very simple materials. Band structure calculations have reached a point of sophistication where the electronic properties of many crystals can be calculated with remarkable precision given the crystal structure and atom spacings. The fundamental challenge of relating the properties of individual atoms to those of a crystalline solid composed of such atoms, particularly the imperfect solid, remains. Ideally the goal of research in this area should be to predict the conditions under which the material forms, its structure, its stability, and its electronic and mechanical properties. But stated this way makes us realize just how primitive is our understanding of such basic matters as interatomic forces, chemical bonding, configurational interactions, and so on. Besides the need for further theoretical developments there is likely to be a need for a long time to come for sensitive experimental determinations of such basic descriptions of the solid as the band structure, the phonon spectra and the Fermi surface with which to test the soundness of theoretical calculations. Other experiments are needed to provide parameter inputs to these calculations such as measurements of intermolecular potentials, charge distributions, and computer experiments on molecular dynamics. In the meantime, to fill the immediate needs of the materials scientist, efforts should be exerted to provide the best available theoretical descriptions of the imperfect solid (e.g. stacking fault energy, stress fields around vacancies, impurity atoms and dislocations). A fruitful approach has been the computer modelling of the defect lattice using interatomic potentials. Much of the groundwork for cooperative experimental-theoretical progress in these areas appears to have been laid and advances in the understanding of the inherent, basic properties of various materials can be expected to emerge steadily in the coming years.

Microscopic Understanding of Phase Transitions

Though the equilibrium crystal structure can be calculated for only a very few simple materials the fundamental ability to predict the abrupt changes in crystal structure that occur as the temperature, pressure or composition is varied is in even worse shape. And the most dramatic phase transition of all, namely melting, is still very much a mystery from a fundamental point of view. If we properly understood melting, we would have much more insight into the roles of interatomic forces and cooperative interactions, etc, in determining the structure and stability of solids. The microscopic mechanisms that bring about phase transition are an object of intense research at present and part of the deep attraction of this study of phase transitions lies in the remarkable quantitative universality of certain general phenomena in the vicinity of second-order phase transitions regardless of the type of material or even of the type of phase transition—the liquid-gas (at critical point), ferromagnetic, ferroelectric, order-disorder (some) and superconducting phase transitions are in certain rather profound ways all the same. In all cases the thermally-driven fluctuations in a particular variable become correlated over increasingly longer ranges as the transition is approached and the time scale of these fluctuations increase markedly. Some consequences of this are the well-known increases in magnetic susceptibility and dielectric constant at the ferromagnetic and ferroelectric transitions, respectively, and critical opalescence at the liquid-gas critical point. While quantitative correspondences between various transitions have been established (the scaling laws) a true microscopic understanding of phase transition mechanisms is lacking—a truly important challenge for materials research and solid state physics in particular. In martensitic transformations, for example, there is a large body of evidence for pre-existing embryos providing sites for nucleation. The nature of these embryos (presumably defect clusters) and the mechanism of interface propagation during transformation are by no means understood. Perhaps equally important is to develop an understanding of phase transition mechanisms in interacting systems, of which the coupling of spins and phonons near the magnetic transition is but one example.

Amorphous, Disordered State

Though fundamental understanding is still in a very primitive state regarding the crystal and electronic structures of crystalline solids it is much worse off as regards the glassy or amorphous state of matter. As was recommended by a recent NMAB panel,* fully-developed conceptual framework for amorphous materials is lacking and close collaboration between experimentalists and theorists is needed for progress to occur. On the theoretical side there is a need for calculations of electronic potentials, energy levels, and transport properties directly applicable to physically realized glass structures. The experimental side calls for better understanding of material preparation and the glassy-to-crystalline transition. The question of what determines the mechanical strength and other physical properties of glasses of various compositions and bond coordinations is pretty well wide open and there persists much uncertainty about the electronic band structure of semiconducting glasses.

Impurity Effects in Solids

When impurities are introduced into an otherwise perfect host crystal in principle all of the properties of the resulting system are modified. The nature and extent of the effect of the impurities depends on their concentration, location and interactions with the host material. In dilute amounts

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*Fundamentals of Amorphous Semiconductors, Report of ad hoc Committee on The Fundamentals of Amorphous Semiconductors, National Materials Advisory Board, NAS/NRC (1972).

the impurities can be viewed as a nonperturbing probe of the microscopic properties of the host (as in spin resonance experiments) but in high concentrations they can lead to new phases (alloys) and phenomena (e.g. order-disorder transitions). Impurities may be desirable, as in most semiconductor phenomena, or undesirable as, for example, in impurity-enhanced optical damage in nonlinear optical materials. Yet, despite the enormous amount of work that has been done on, for example, impurity effects in semiconductors, a general microscopic understanding and theory of the effects of impurities on material properties is lacking. The dilute limit, while theoretically simplest, is experimentally the most difficult, while the converse is true for high-impurity concentrations. The directions for improvement on these problems are obvious. The intermediate domain, in which impurity-impurity interactions are no longer negligible, constitutes a prime challenge to both theory and experiment. Recent experiments have shown the existence of collective impurity modes such as phonons, excitons, and magnons at intermediate concentration levels. Theories are needed to explain the emergence of this behavior from the single impurity behavior at low concentrations and to distinguish it from the mixed crystal or alloy behavior at high concentrations. Experiments are needed on systems where impurity-host interaction strengths are sufficiently weaker than impurity-impurity interactions to compensate in a controlled way for the numerical superiority of the former. More consideration should be given to systems with simple structured and/or inert hosts, such as helium and the other rare gas solids, so as to provide theoretically tractable, experimentally accessible model systems for impurity effects. The possibility of long-range order (e.g. magnetic) in the impurities which is absent from the host is particularly intriguing. Properly controlled impurity experiments in the nondilute range could open new opportunities for direct observation of microscopic interactions. Progress along these lines has already been made in thin-film studies on magnetic impurities in nonmagnetic, metallic hosts. Similar experiments on optical, elastic, and dielectric properties promise exciting results. A particular lingering puzzle is the role of impurity excitons in semiconductor laser action. Optical studies have suggested the presence of excitonic molecules and have stimulated speculation on the possibility of an excitonic liquid or even a solid phase. Another continuing controversy concerns the role of interstitial impurities in increasing the low-temperature yield strength (thereby enhancing brittleness) of body-centered cubic metals. One camp argues that lattice friction stress of the pure metal is inherently large at low temperature, while another argues that interstitials introduce lattice distortion which is especially effective at low temperature. Although sophisticated experiments are needed here, theoretical calculations based on interatomic forces should help decide the issue.

One- and Two-Dimensional Systems

Until fairly recently calculations of physical phenomena in one- or two-dimensional systems were considered to be of mainly academic interest. Onsager’s famous exact solution to the two-dimensional Ising model provided inspiration to solid state physicists and engendered the hope for eventual similar success in three-dimensional, or "real" systems. Within the past four or five years, however, a variety of magnetic, superconducting and resistive materials have been prepared which exhibit exceedingly large anisotropies in their thermodynamic, transport, and collective properties. The anisotropies are sufficiently large that the microscopic interactions along a line or within a plane may be several orders of magnitude larger than in the transverse directions. For example, tetragonal crystals of the K_2NiF_4 family exhibit in-plane magnetic exchange forces several thousand times larger than the out-of-plane exchanges, with the results that below about 100ºK truly two-dimensional long range magnetic order occurs. Neutron susceptibility and optical experiments have confirmed the two-dimensional nature of the spin dynamics (magnons) and the critical behavior as well. Similar striking behavior in one-dimensional antiferromagnetism has been observed. Layered structure transition metal dichalcogenides (MoS_2, etc.) have long been recognized as effective lubricants. More recently they have been found to be essentially two-dimensional superconductors, whose properties can be altered markedly by chemically changing the spacing between layers. Certain organo-metallic complexes have exhibited one-dimensional manifestations of antiferromagnetism and the metal-insulator transition. These discoveries have enkindled lively theoretical and experimental interest in the physics of less-than-three dimensions. Consequences of extreme anisotropy of microscopic interactions must be explored more fully. The effects of lower dimensionality on collective modes, electron and heat transport must be understood. Particularly intriguing is the effect of a microscopic upper limit to the correlation length in certain directions on the critical properties near phase transitions in lower dimensional systems. While some magnetic transitions have been studied, virtually nothing has been done on structural, order-disorder or ferroelectric transitions in less than three dimensions. Improved understanding of the physics and chemistry of two-dimensional systems is essential to the eventual understanding of catalysis. Because of the extreme anisotropy in bonding strength, study of the mechanical behavior of the layered structure materials could lead to superior lubricants or high strength components, as already demonstrated in graphite. In usual powder form graphite is a widely-used lubricant. Through processing of precursor polymer filaments, dense and highly oriented graphite fibers have been prepared which exhibit axial strengths that are a significant fraction of the theoretical strength.

Although in some ways fundamentally different, thin films and filaments of otherwise three-dimensional materials are a subject of renewed interest to solid state physics. The fabrication of structures which extend only few tens of angstroms in one or two directions has made clear the need for more careful experiments and sophisticated interpretations to understand the physics of such structures. Two indicative examples are the observation of a nearly five-fold increase in the superconducting transition temperature in thin Al films and the increased sound attenuation coefficient in small diameter glass fibers.

Physics and Chemistry of Surfaces

Surfaces are possibly one of the most fruitful research, areas in materials science. Knowledge at the most fundamental level in this area can be expected to have relevance to almost all uses of materials, from the processing and reliable performance of integrated circuits to the corrosion of structural components, from frictional wear and tear to catalysis and flammability, from crystal growth to adhesion. The variety and complexity of surfaces and surface layers are at least comparable to the variety and complexity of bulk properties but our level of understanding of surfaces is, in contrast, in its infancy.

While the aim is to develop a more sophisticated understanding of the electronic and chemical properties of surfaces, our present level of ignorance is illustrated by the fact that these properties are very sensitive to the detailed ways in which atoms are positioned at the surface, and in general these positions are not known. Surface properties are related to the properties of the underlying bulk but in ways which are not often clear. And though it can be said that bulk properties are understood by-and-large in principle, if not always in detail, this is not true of many of the surface properties where the broad outlines of the phenomenology are only now being drawn. This phenomenology concerns, for example, the details and statistical mechanics of surface topology, local bond and electronic structures, the energy states of electrons at surfaces, models for nucleation and growth, and so on.

Surfaces offer an extra degree of freedom for arrangement of atoms statistically on the lattice sites. The statistical mechanics of this situation, extending with three dimensions over several atomic layers, needs considerable development. While the roughness of a surface on the atomic scale has a major impact on adsorption, surface diffusion and crystal growth processes, very little is yet known about the details of the role of surface roughness in these processes.

The electronic properties of surfaces in simple systems need considerable attention. There is some controversy about the extent to which surfaces can be treated as an extension of the bulk or whether the discontinuity in properties at the surface is sufficiently great to require new concepts and analytical procedures. Our theoretical models for surface electronic properties, surface relaxation and surface structure are in a rudimentary state at present. The extent to which surface states on semiconductors are an intrinsic property of the surface or associated with surface impurities is under debate. Surface states occur both at free surfaces and at interfaces, such as the silicon-silicon oxide interface. It has recently been shown that various surface states on semiconductors correlate with various surface structures as revealed by low energy electron diffraction.

Surface nucleation, vapor deposition, adsorption, and surface contamination, topics with clear practical significance, are currently being investigated experimentally in detail for a variety of systems, with emphasis on the simpler systems. Much more work in this area needs to be done. The kinetics and thermodynamic properties of vapor deposits can be obtained by mass spectrometric methods and the distribution of clusters on the surface can be determined by diffraction methods. Simple classical surface nucleation theory is inadequate to account for the measurements and major modifications of the theory appear to be necessary. Adsorbed atoms can be identified using Auger spectroscopy even at a small fraction of a monolayer coverage. Auger spectroscopy coupled with ion bombardment can be used for profiling, to get at bulk composition profiles below the surface. Low energy electron diffraction is just entering the quantitative stage where the position of surface atoms can be determined with some accuracy. These methods are also being used extensively to monitor the cleanliness and structure of surfaces as well as to investigate production problems involving contamination at surfaces. The electronic and chemical properties of surfaces and adsorbed species are being investigated by a variety of methods. Photoelectron spectroscopy and UV photoemission spectroscopy are used to obtain band structure information. Electronic and chemical bonding information can be obtained from ion neutralization spectroscopy. IR reflection spectroscopy gives information about chemical bonding, and information about deep electronic levels can be also obtained from the analysis of Auger spectra.

The techniques developed for surface research, such as ion mass analysis and Auger spectroscopy, are providing the best, and often the only, methods available for investigating materials problems associated with thin films, grain boundary segragation, interdiffusion phenomena, and trace analysis. The trend towards miniaturization in electronics resulting from economic, reliability and high frequency considerations points towards growing importance of surfaces. The concepts of miniaturization are best embodied in the technology of large scale integrated circuits where surface and grain boundary diffusion often dominate over bulk diffusion processes. This trend is expected to continue, particularly as optical microcircuitry is developed.

The understanding of catalytic processes is not detailed in most cases. Considerable qualitative insight is available, but the roles of surface structure, surface defects, surface geometry, surface electronic properties and even the bulk properties are not understood in detail.

Significant advances have been made in the area of adhesion, where the understanding of the role of adlayers and their interaction has contributed significantly. Friction is understood in some detail, especially the role and interaction of the asperities in sliding contact, but the process is difficult to treat from a fundamental standpoint, let alone circumvent in practice. From a practical point of view, the lubrication of sliding contacts is fairly well understood. Cold welding can be a serious problem in electrical contacts. Erosion, corrosion and contamination of electrical contacts as a result of arcing remain serious problems.

Deeper knowledge of the behavior of surfaces can also be expected to improve our control over the important practical problem of corrosion—the interaction of a material with its environment. The presence of water or an electrolyte solution changes the physics and chemistry of metal surfaces significantly. The surface energy is altered and becomes a strong function of the charge in the electrical double layer at the metal/solution interface. The equilibrium surface structure may be different from that in the presence of the metal's own vapor or a vacuum and it presents extra problems in that the interface is not readily examined in situ. Some metals, e.g., silver, undergo surface rearrangement in aqueous solution at room temperature. Alloys generally undergo a change in their equilibrium or steady-state surface composition. The atomistics of the above are poorly understood. There is much ignorance regarding the effects of surface stress, defect structure, and nonequilibrium conditions on the reactivity of metal surfaces.

Physical Properties of Polymeric Materials

Polymeric substances, whether natural such as cotton, wool, and silk, or synthetic, including rubber, rayon and celluloid, owe their remarkable physical and chemical properties which set them apart from a host of well recognized materials to the very long chain molecules of which they are made. Recognition of the key role of long chain molecules was one of the singular discoveries of this century. It led to intense research to discover how variation in the structure of these giant molecules, through new approaches in chemical synthesis, could be invoked to cause valuable changes in physical properties. Yet to put the structure-property relationship of polymeric materials on a firm, fundamental, quantitative base remains a prime challenge to materials research, akin in complexity to the parallel challenge posed by amorphous inorganic materials, perhaps more so.

Collective Behavior

Perhaps the single most fruitful concept in solid state physics has been that of the collective mode or elementary excitation; this concept has permitted the handling of complex many (10^{23}) body systems in terms of a very few degrees of freedom. The basic idea is to regard the structure and composition of the system as given and to seek its responses to various types of disturbance. The complete set of these responses form the so-called “normal modes” or “elementary excitations” of the system in terms of which many of its static and dynamic properties can be expressed. Since a single elementary excitation involves the participation of all the atoms in the system, the concept is quite fruitful in elucidating the cooperative behavior among large numbers of particles which result in a particular phenomenon or property. As was briefly indicated in the discussion of phase transitions, the collective mode concept is quite fruitful in describing even anomalous material properties. The elementary excitation concept has become so familiar to physicists (the words phonon, plasmon, magnon, etc. are well incorporated into the field’s vocabulary) that it may not often be recognized as still having potential for significant growth. However there are at least two directions in which extensions of the concept should prove of significant value: (1) nonlinearities and interactions among elementary excitations and (2) elementary excitations in systems lacking long range order. Recent experimental advances have permitted more precise and complete direct study of the more familiar excitations on the one hand, and generation, detection and study of some new excitations on the other. In the former catagory are included inelastic scattering (both light and neutrons) acoustic, magneto-optic and certain solid state plasma experiments. The latter includes super high-frequency phonon and second sound generation by quasiparticle recombination in superconductors; the launching of stable finite amplitude pulses of both mechanical (solitons) and electromagnetic nature (self-induced transparency); propagating electroacoustic domains in semiconductors, etc. For the future better understanding can be expected of the interactions among these excitations leading to optimized manipulation of such interactions for energy or information transfer.

Perhaps less straightforward but certainly no less important is the second direction: studies of elementary excitations in systems lacking long range order. This includes obviously, amorphous solids and liquids, where effort of this kind has been underway for some time. Already, for example, some microscopic understanding of electronic, optical and acoustic properties of such materials has emerged. Recent generalizations of the hydrodynamic equations to shorter length and higher frequency domains have revealed the smooth transition from collective, phonon-like behavior to diffusive and even single particle behavior in liquids. Some of these trends should also be evident in visco-elastic solids, but the picture is not yet clear. Similar mathematical techniques have been employed to describe elementary excitations in the paramagnetic (disordered) phase of a spin system. The collective modes of the liquid crystal state are under present investigation and should illuminate that important intermediate regime between well-developed long range order (crystal) and the more transient short range order (liquid).

A most exciting possibility lies in the extension of the collective mode concept to large but finite structures, particularly to macromolecules. From the point of view that a large molecule approximates a small solid, the existence of collective motions within the molecule is clear. However, the detailed nature of such excitations and their role in transport of charge, strain, spin, etc. within the molecule remain challenges to both theorist and experimenter in solid state physics. The hope for a true science base for “molecular engineering” largely rests on progress in this direction.

Nonequilibrium Systems

Despite the several unresolved problems indicated above, our basic understanding of the physics of materials under equilibrium conditions is far ahead of that for nonequilibrium systems. While the reasons are not hard to find (such as the inapplicability of thermodynamics and statistical mechanics), the increasing importance of nonequilibrium phenomena requires that substantial effort be expended to alleviate these deficiencies. Lasers and negative resistance semiconductor devices are familiar examples of nonequilibrium physics in action. Recent progress in understanding the transient and threshold behavior has illuminated analogies with equilibrium second-order phase transitions. It is intriguing to investigate more general instabilities such as hydrodynamic, magneto-hydrodynamic, and plasma phenomena from this point of view. The problem of turbulence is perhaps the most challenging and important of these. Auto-catalytic chemical reaction systems give rise to large spatial and temporal variations in composition.

The familiar convective instability can cause extreme problems in crystal growth from the melt. Indeed the behavior of the atmosphere, the oceans and even the earth's crust are strongly influenced by such hydrodynamic instabilities. Instabilities in both gaseous and solid state plasmas have received much attention but are not fully understood.

On a slower time scale understanding metastable states and structures in solids and solid solutions (including spinodal decomposition) should benefit from attacks on these problems.

With new laser techniques, detailed investigation of materials under extreme transient conditions (shock waves, high electric, magnetic or optical fields) can be studied in real time with resolution of $\sim 10^{-12}$ seconds and longer. Scattering, absorption and fluorescence experiments which have proved so valuable in guiding theories of materials at equilibrium, should soon begin to do the same for nonequilibrium systems. A foretaste of what might be in store is the use of these fast laser pulses for studying short-lived excited states of radicals and molecules with consequent insights into the mechanisms of chemical reactions.