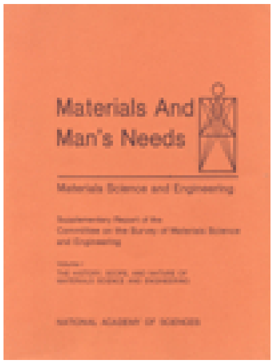

Materials and Man's Needs: Materials Science and Engineering -- Volume I, The History, Scope, and Nature of Materials Science and Engineering

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

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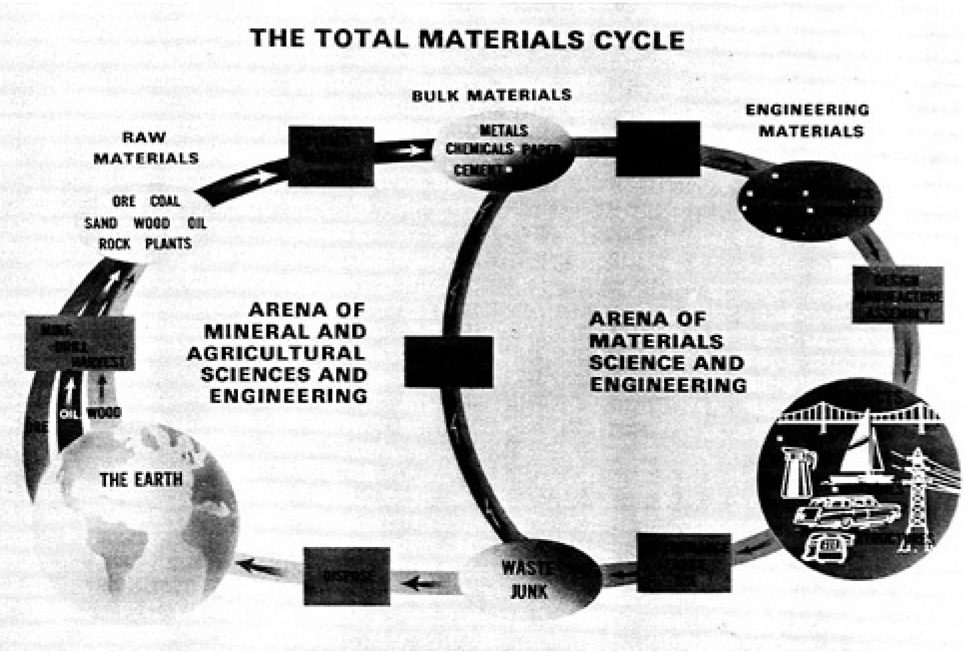
THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

MATERIALS AND MAN'S NEEDS

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

THE HISTORY, SCOPE, AND NATURE OF MATERIALS SCIENCE AND ENGINEERING

NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D.C. 1975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MATERIALS AND MAN'S NEEDS

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

VOLUME I

THE HISTORY, SCOPE, AND NATURE OF MATERIALS SCIENCE AND ENGINEERING

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 priorities 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

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

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Volume I The History, Scope, and Nature of Materials Science and Engineering
Chapter 1; Materials and Society
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
Chapter 4; National Objectives and the Role of Materials Science and Engineering
Chapter 5: Priorities in Materials Research
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MATERIALS SCIENCE AND ENGINEERING AS A MULTIDISCIPLINE

CHAPTER 1
MATERIALS AND SOCIETY*

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* This chapter is primarily the work of COSMAT Panel I, particularly by the co-chairmen, Cyril S.Smith and Melvin Kranzberg.

CHAPTER 1

MATERIALS AND SOCIETY

INTRODUCTION

The field of materials is immense and diverse. Historically, it began with the emergence of man himself, and materials gave name to the ages of civilization. Today, the field logically encompasses the lonely prospector and the advanced instrumented search for oil; it spreads from the furious flame of the oxygen steelmaking furnace to the quiet cold electrodeposition of copper; from the massive rolling mill producing steel rails to the craftsman hammering out a chalice or a piece of jewelry; from the smallest chip of an electronic device to the largest building made by man; from the common paper-bag to the titanium shell of a space ship; from the clearest glass to carbon black; from liquid mercury to the hardest diamond; from superconductors to insulators; from the room-temperature casting plastics to infusible refractories (except they can be melted today); from milady's stocking to the militant's bomb; from the sweating blacksmith to the cloistered contemplating scholar who once worried about the nature of matter and now tries to calculate the difference between materials.

Materials by themselves do nothing; yet without materials man can do nothing. Nature itself is a self-ordered structure which developed through time by the utilization of the same properties of atomic hierarchy that man presides over in his simple constructions.

One of the hallmarks of modern industrialized society is our increasing extravagance in the use of materials. We use more materials than ever before, and we use them up faster. Indeed, it has been postulated that, assuming current trends in world production and population growth, the materials requirements for the next decade and a half could equal all the materials used throughout history up to date.[1] This expanding use of materials is itself revolutionary, and hence forms an integral part of the "materials revolution" of our times.

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[1] The most popular—and most terrifying-of the projections prophesying dire results of the current trends in materials use in relation to present rates of population growth is to be found in the report of the Club of Rome's Project on the Predicament of Mankind. See Donella H.Meadows, Dennis L. Meadows, Jorgen Randers, and William W.W.Behrens III, The Limits to Growth, Universe Books, New York (1972).

Not only are we consuming materials more rapidly, but we are using an increasing diversity of materials. A great new range of materials has opened up for the use of 20th-century man: refractory metals, light alloys, plastics, and synthetic fibers, for example. Some of these do better, or cheaper, what the older ones did; others have combinations of properties that enable entirely new devices to be made or quite new effects to be achieved. We now employ in industrial processes a majority of the ninety-two elements in the periodic table which are found in nature, whereas until a century ago, all but 20, if known at all, were curiosities of the chemistry laboratory.[2] Not only are more of nature's elements being put into service, but completely new materials are being synthesized in the laboratory. Our claim to a high level of materials civilization rests on this expanded, almost extravagant utilization of a rich diversity of materials.

This extravagance is both a product of advances in materials and a challenge in its future growth. The enlarged consumption of materials means that we will have to cope increasingly with natural-resource and supply problems. Mankind is being forced, therefore, to enlarge its resource base—by finding ways to employ existing raw materials more efficiently, to convert previously unusable substances to useful materials, to recycle waste materials and make them reusable, and to produce wholly new materials out of substances which are available in abundance.

The expanded demand for materials is not confined to sophisticated space ships or electronic and nuclear devices. In most American kitchens are new heat-shock-proof glasses and ceramics—and long-life electric elements to heat them; the motors in electric appliances have so-called oilless bearings which actually hold a lifetime supply of oil, made possible by powder metallurgy; the pocket camera uses new compositions of coated optical glass; office copy-machines depend on photoconductors; toy soldiers are formed out of plastics, not lead; boats are molded out of fiberglass; the humble garbage can sounds off with a plastic thud rather than a metallic clank; we sleep on synthetic foam mattresses and polyfiber pillows, instead of cotton and wool stuffing and feathers; we are scarcely aware of how many objects of everyday life have been transformed—and in most cases, improved—by the application of materials science and engineering (MSE). Moreover, as with a rich vocabulary in literature, the flexibility that is engendered by MSE greatly increases the options in substitutions of one material for another.

Quite often the development of a new materials or process will have effects far beyond what the originators expected. Materials have somewhat the quality of letters in the alphabet in that they can be used to compose many things larger than themselves; amber, gold jewelry, and iron ore inspired commerce and the discovery of many parts of the world; improvements in optical glass lies behind all the knowledge revealed by the microscope; conductors, insulators, and semiconductors were needed to construct new communication systems which today affect the thought, work, and play of everyone. Alloy steel permitted the development of the automobile; titanium the space program. The finding of a new material was essential for the growth of the

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[2] Sir George P.Thomson, "…a New Materials Age," General Electric Forum XI, 1 (Summer 1965) 5.

laser, the social uses of which cannot yet be fully imagined. In these, as in hundreds of other cases, the materials themselves are soon taken for granted, just as are the letters of a word. To be sure, the ultimate value of a material lies in what society chooses to do with whatever is made of it, but changes in the “smaller parts” reacting responsibly to larger movements and structures make: it possible to evolve new patterns of social organization.

The transitions from, say, stone to bronze and from bronze to iron were revolutionary in impact, but they were relatively slow in terms of the time scale. The changes in materials innovation and application within the last half century occur in a time span which is revolutionary rather than evolutionary.

The materials revolution of our times is qualitative as well as quantitative. It breeds the attitude of purposeful creativity rather than modification of natural materials, and also a new approach—an innovative organization of science and technology. The combination of these elements which constitutes materials science and engineering (MSE) is characterized by a new language of science and engineering, by new tools for research, by a new approach to the structure and properties of materials of all kinds, by a new interdependence of scientific research and technical development, and by a new coupling of scientific endeavor with societal needs.

As a field, MSE is young. There is still no professional organization embodying all of its aspects, and there is even some disagreement as to what constitutes the field. One of the elements which is newest about it is the notion of purposive creation. However, MSE is responsive as well as creative. Not only does it create new materials, sometimes before their possible uses are recognized, but it responds to new and different needs of our sophisticated and complex industrial society. In a sense, MSE is today’s alchemy. Almost magically, it transmutes base materials, not into gold—although it can produce gold-looking substances—but into substances which are of greater use and benefit to mankind than this precious metal. MSE is directed toward the solution of problems of a scientific and technological nature bearing on the creation and development of materials for specific uses; this means that it couples scientific research with engineering applications of the end-product: one must speak of materials science and engineering as an “it” rather than “them.”

Not only is MSE postulated on the linkage of science and technology, it draws together different fields within science and engineering. From technology, MSE brings metallurgists, ceramists, electrical engineers, chemical engineers; from science it embraces physicists, inorganic chemists, organic chemists, crystallographers, and various specialists within those major fields.

In its development, MSE not only involved cooperation among different branches of science and engineering, but also collaboration among different kinds of organizations. Industrial corporations, governmental agencies, and universities have worked together to shape the outlines and operations of this new “field.”

In recent years there has been a marked increase in the liaison between industrial production and industrial research, and between research in industry and that in the universities. The researcher cannot ignore problems of production, and the producer knows that he can get from the scientist suggestions for new products and sometimes help for difficulties. It should be noticed that MSE has come about by the aggregation of several different specialties that were earlier separate, not, as so often happens, by growth of increased diversity within a field which keeps some cohesion. This change is just as much on the industrial side as it is on the academic. Industry continually uses its old production capabilities on new materials, and the scientist finds himself forced to look at a different scale of aggregation of matter.

Most of the work on materials until the 20th century was aimed at making the old materials available in greater quantity, of better quality, or at less cost. The new world in which materials are developed for specific purposes (usually by persons who are concerned with end-use rather than with the production of the materials themselves) introduces a fundamental change, indeed. Heretofore, engineers were limited in their designs to the use of materials already “on the shelf.” This limitation no longer applies, and the design of new materials is becoming a very intimate part of almost every engineering plan. MSE interacts particularly well with engineers who have some application in mind. It often reaches the general public through secondary effects, such as negatively via the pollution which results from mining, smelting, or processing operations, and positively via the taken-for-granted materials that underly every product and service in today’s complicated world. The provision of materials for school children and mature artists is one of the more positive contacts with the public, Of course, most materials existed long before MSE aided in their development, but now it does provide the guidelines for future change.

The rising tide of “materials expectations” is not for the materials themselves, but for things which of necessity incorporate materials. That materials are secondary in most end-applications is obvious from the name applied to the materials that remain when a machine or structure no longer serves its purpose— “junk.” There is, however, at least one positive direct contact, that of waste-material processing; for city waste disposal is a very challenging materials-processing problem, especially if the entire cycle from production, use, and reuse of materials can be brought into proper balance.

As one cynical observer put it, “For the first two decades of its existence, materials science and engineering was engaged in producing new and better products for mankind; the major task of materials science and engineering for the next two decades is to help us get rid of the rubbish accumulated because of the successes of the past twenty years.”

IMPORTANCE OF MATERIALS TO MAN

Materials are so ubiquitous and so important to man’s life and welfare that we must obviously delimit the term in this survey, lest we find ourselves investigating nearly every aspect of science and technology and describing virtually every facet of human existence and social life. Unless we limit our scope, all matter in the universe will inadvertently be encompassed within the scope of our survey.

But matter is not the same as material. Mainly we are concerned with materials that are to become part of a device or structure or product made by man. The science part of MSE seeks to discover, analyze and understand the nature of materials, to provide coherent explanations of the origin of the properties that are used, while the engineering aspect takes this basic knowledge and whatever else is necessary (not the least of which is experience) to develop, prepare, and apply materials for specified needs, often the most advanced objectives of the times. It is the necessarily intimate relationship between these disparate activities that to some extent distinguishes MSE from other fields and which makes it so fascinating for its practitioners. The benefits come not only from the production of age-old materials in greater quantities and with less cost—an aspect which has perhaps the most visible influence on the modern world, but it also involves the production of materials with totally new properties. Both of these contributions have changed the economy and social structure, and both have come about in large measure through the application of a mixture of theoretical and empirical science with entrepreneurship. And just as the development of mathematical principles of design enabled the 19th-century engineer to test available materials and select the best suited for his constructions, so the deeper understanding of the structural basis of materials has given the scientist a viewpoint applicable to all materials, and at every stage from their manufacture to their societal use and ultimate return to earth.

The production of materials has always been accompanied by some form of pollution, but this only became a problem when industrialization and population enormously increased the scale of operation. Longfellow’s poem contains no complaint about the smoke arising from the village smithy’s forge; if one of today’s poets would attempt to glorify the blacksmith’s modern counterpart, he would undoubtedly describe the smoke belching forth from the foundry, but there would be no mention of spreading chestnut trees because all those within a half-mile’s radius would long ago have withered from the pollution of the surrounding neighborhood. The simple fact is that an industrial civilization represents more activity, more production, and usually more pollution, even though the pollution attributable to each unit produced may be sharply decreased.

The utilization of materials, as well as their manufacture, also generates pollution. Those of us living in affluent, highly industrialized countries enjoy the benefits of a “throw-away” society. The problem arises from the fact that many of the products we use are made from materials which are not strictly “throw-awayable.” Natural processes do not readily return all materials to the overall cycle, and in the case of certain mineral products, we can sometimes find no better way of disposing of scrap than to bury it back in the earth from which we had originally extracted it at great trouble and expense. Proposals for reuse or recycling often founder upon public apathy—but this is changing, and MSE has an important role to play.

The moral and spiritual impact of materials on both consumer and producer is both less visible and more debatable. To those reared in a Puritanical ethic of self-denial, the outpouring of materials goods would seem almost sinful, as would the waste products of a throw-away society. Such conspicuous consumption would seem almost immoral in a world where so many people are still lacking basic material essentials. A more sophisticated objection might be that the very profusion of materials presents modern man with psychological dilemmas. We are presented with so many options that we find it difficult to choose among them.[3]

It might be surprising to some that the question of the debasement of the materials producer should even be raised. Scientists have long claimed that their pursuit of an understanding of nature is innocent, and technologists have always assumed that their gifts of materials plenty to mankind would be welcomed. Hence, it has come as a shock to them during the past few years that the benefits of science and technology have been questioned. Both science and technology have been subjected to criticism from highly articulate members of the literature subculture, as well as from within their own ranks, regarding their contributions to mankind's destructive activities and to the deterioration of the environment.[4]

To those engaged in materials production and fabrication, it may be disconcerting to realize that for a fair fraction of human history their activities have been viewed with suspicion and downright distaste by social thinkers and by the general public. The ancient Greek philosophers, who set the tone for many of the attitudes still prevalent throughout Western Civilization, regarded those involved in the production of material goods as being less worthy than agriculturists and others who did not perform such mundane tasks. Greek mythology provided a basis for this disdain: the Greek Gods were viewed as idealistic models of physical perfection; the only flawed immortal was the patron god of the metalworker, Hephaestus, whose lameness made him the butt of jokes among his Olympian colleagues, (But he got along well with Aphrodite, another producer!)

Throughout ancient society the most menial tasks, especially those of mining and metallurgy, were left to slaves. Hence, the common social attitude of antiquity, persisting to this day in some intellectual circles, was to look down upon those who worked with their hands. Xenophon[5] stated the case in this fashion: "What are called the mechanical arts carry a social stigma and are rightly dishonored in our cities. For these arts damage the bodies of those who work at them or who act as overseers, by compelling them to a sedentary life and to an indoor life, and, in some cases, to spend the whole day by the fire. This physical degeneration results also in deterioration of the soul. Furthermore, the workers at these trades simply have not got the time to perform the offices of friendship or citizenship. Consequently they are looked upon as bad friends and bad patriots, and in some cities, especially the warlike ones, it is not legal for a citizen to ply a mechanical trade."

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[3] This is one of the major theses of Alvin Toffler, Future Shock, Random House, New York (1970).

[4] There is a formidable literature of anti-science and anti-technology. Not only are there the attacks of the counter-culture (represented by the writings of Theodore Roszak, Paul Goodman, and Herbert Marcuse), but more thoughtful observers, such as Lewis Mumford, have attacked the spirit and practice of science and technology in the modern world. Among scientists, the work of Barry Commoner (The Closing Circle, Knopf, New York (1971)) stands out in this regard.

[5] Oeconomicus, Book IV.

The ancients appreciated material goods but they did not think highly of those who actually produced them. In his life of Marcellus, Plutarch delivered this critical judgment, “For it does not of necessity follow that, if the work delights you with its grace, the one who wrought it is worthy of esteem.” The current apprehension concerning dangers to the environment from materials production might result in materials scientists and engineers being regarded with similar suspicion today.

But there is yet a subtler way in which the triumphs of MSE might threaten the spirit of Western man. Advances in materials have gone beyond the simple task of conquering nature and mastering the environment. MSE attempts to improve upon nature. In a sense, this represents the ancient Greek sin of hubris, inordinate pride, where men thought they could rival or even excel the gods—and retribution from the gods followed inevitably. This may also be “original sin,” the Christian sin of pride, which caused Adam’s fall. By eating the fruit of the tree of knowledge, Adam thought that he would know as much as God. Conceivably, by endeavoring to outdo nature modern man is preparing his own fall. Or perhaps his new knowledge will lead to control as well as power, and a richer life for mankind.

MATERIALS IN THE EVOLUTION OF MAN AND IN PREHISTORY

The very essence of a cultural development is its interrelatedness. This survey places emphasis on materials, but it should be obvious that materials per se are of little value unless they are shaped into a form that permits man to make or do something useful, or one that he finds delightful to touch or to contemplate. The material simply permits things to be done because of its bulk, its strength or, in more recent times, its varied combinations of physical, chemical, and mechanical properties. The internal structure of the material that gives these properties is simply one stage in the complex hierarchy of physical and conceptual structures that make up the totality of man’s works and aspirations.

We do not know exactly when our present human species, homo sapiens, came into being, but we do know that materials must have played a part in the evolution of man from more primitive forms of animal primates. It was the interaction of biological material and cultural processes that differentiated man from the rest of the animal world.[6] Other animals possess great physical advantages over man: the lion is stronger, the horse is faster, the giraffe has a greater reach for food. Nevertheless, man possesses certain anatomical features which prove particularly useful in enabling him to deal with his environment.[7]

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[6] Theodosius Dobzhansky, Mankind Evolving: The Evolution of the Human Species, Yale University Press, New Haven (1962), A popular account is to be found in John E.Pfeiffer, The Emergence of Man, Harper and Row, New York (1972).

[7] See V.Gordon Childe, Man Makes Himself, Mentor Edn., New York (1951) chs. 1–2; and Childe, What Happened in History, Penguin edn., New York (1946) ch. 1.

Modern physical anthropologists believe that there is a direct connection between such cultural traits as toolmaking and tool-using, and the development of man's physical characteristics, including his brain and his hand.[8] Man would not have become Man the Thinker (homo sapiens) had he not at the same time been Man the Maker (homo faber). Man made tools, but tools also made man. Perhaps man did not throw stones because he was standing up; he could have learned to stand erect the better to throw stones.

It is probable that the earliest humans used tools rather than made them, that is, they selected whatever natural objects were at hand for immediate use before they anticipated a possible future task and prepared the tools for it. Once this idea was formulated and man began to discover and test out things for what they could do, he found natural objects—sticks, fibers, hides—and combined materials and shapes to serve his purposes. He tried bones and horn, but the hardest and densest material at hand was stone. When he further learned how to form materials as well as select them, and to communicate his knowledge, civilization could begin; it appears there was a strong evolutionary bias towards anatomical and mental types that could do this. While the early stages still remain the realm of hypothesis, there is general agreement that it was over two million years ago when a pre-human hominid began to use pebbles or stones as tools, though the shaping of specialized tools came slowly.

The recognition that there had been a cultural level to which we now give the name of Stone Age—itself a tribute to the importance of materials in man's development—did not occur until well into the 19th century. When, about 1837, the Frenchman Boucher de Perthes propounded the view that some oddly-shaped stones were not "freaks of nature" but were the result of directed purposeful work by human hands, he was ridiculed. Only when the vastness of geological time scales was established and it became possible to depart from a literal interpretation of biblical genesis could credence be given to the notion that these stones were actually tools.[9]

Some of the features of today's materials engineering can already be seen in the selection of flint by our prehistoric forebears as the best material for making tools and weapons. Availability, shapability, and serviceability are balanced. The brittleness of flint enabled it to be chipped and flaked into specialized tools, but it was not too fragile for service in the form of scrapers, knives, awls, hand axes, and the like. The geopolitical importance of material sources also appears early. It is perhaps not surprising that we find the most advanced early technologies and societies developing where

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[8] See S.L.Washburn, "Speculations on the Interrelations of the History of Tools and Biological Evolution," The Evolution of Man's Capacity for Culture, J.N.Spuhler, ed., Wayne University Press, Detroit (1959) 21–31; A.Brues, "The Spearman and the Archer—An Essay on Selection in Body Build," American Anthropologist, 61 (1959)457–69. See also The Dawn of Civilization, McGraw-Hill, New York (1961).

[9] Robert F.Heizer, "The Background of Thomson's Three-Age System," Technology and Culture, III, 3 (Summer 1962) 259–66.

good-quality flint was available. It may even be, as Jacobs has surmised[10], that cities arose from flint-trading centers and that the intellectual liveliness accompanying the cultural interchange of travellers then created the environment in which agriculture originated.

The pattern of human settlement from prehistoric times to our contemporary world has been determined in large measure by the availability of materials and the technological ability to work them.

Man could survive successive ice ages in the Northern Hemisphere without migrating or developing a shaggy coat like the mammoth because he had found some means of keeping himself warm—with protective covering from the skins of animals which, with his wooden and stone weapons, he could now hunt with some degree of success, but also, perhaps principally, by the control of fire, which became one of his greatest steps in controlling his environment. By the beginning of Palaeolithic (early Stone Age) times—between 800,000 and 100,000 years ago—man could produce fire at will by striking lumps of flint and iron pyrites against each other to produce sparks with which tinder, straw, or other flammable materials could be ignited.

Man's control and use of fire had immense social and cultural consequences. With fire he could not only warm his body but could also cook his food, greatly increasing the range of food resources and the ease of its preservation. Claude Levi-Strauss, the French anthropologist famous for his "structuralist" approach to culture, claims that the borderline between "nature" and "culture" lies in eating one's meat raw or eating it cooked.[11] By their role in producing and fueling fires, materials thus played a significant part in the transition from "animal-ness" to "human-ness," but more than that, fire provided a means of modifying and greatly extending the range of properties available in materials themselves.

Every cultural conquest, such as the use of fire, requires other cultural developments to make its use effective, and it also has unanticipated consequences in totally unforeseen areas. Containers were needed for better fire and food. The invention of pots, pans, and other kitchen utensils made it possible to boil, stew, bake, and fry foods as well as to broil them by direct contact with the fire. The cooking itself, and the search for materials to do it in, was perhaps the beginning of materials engineering! Furthermore, though the molding and fire hardening of clay figurines and fetishes had preceded the useful pot, it was the latter that, in the 8th millenium B.C., gave rise to the development of industry. Clay was the first inorganic material to be given completely new properties as a result of an intentional operation upon it by human beings. Though stone, wood, hides, and bone had earlier been beautifully formed into tools and utensils, their substance had remained essentially unchanged. The ability to make a hard stone from soft and moldable clay not only unfolded into useful objects, but the realization that man could change the innermost nature of natural materials must have had a profound impact upon his view of his powers; it gave him confidence to search for new materials at an ever increasing rate.

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[10] Jane Jacobs, The Economy of Cities, Random House, New York (1969).

[11] Claude Lévi-Strauss, The Raw and the Cooked; Introduction to a Science of Mythology, Harper and Row, New York (1969).

It was in the decoration of pottery that man first experimented with the effects of fire upon a wide range of mineral substances. Glazing, the forerunner of glass, certainly came therefrom, and it is probable that experiments with mineral colors on pottery led to the discovery of the reduction of metals from their ores toward the end of the 5th millennium B.C. Even earlier, man's urge to art had inspired the discovery and application of many metallic minerals as pigments.[12]

From late Paleolithic times come the great cave paintings representing hunting scenes in realistic detail, executed with such mastery that, when they were discovered by chance in the caves at Altamira, Spain in 1879 and later in Lascaux, France, many found it difficult to believe that they had been done by primitive man. These paintings provide the earliest evidence of man's awareness of the special properties of iron ore, manganese ore, and other minerals. He sensed qualitative differences that depended on chemical and physical properties quite invisible to him, on which eventually could be based a metallurgical industry.

Even before he learned to paint, early man had sensitively used the properties of other materials in art. He had made sculpture in ivory, stone, rock, clay, and countless more-perishable materials. Though it is often said that his ability to do this came from the increased leisure time released by the efficiency of his hunting following the development of tools and weapons, it is more likely that the exercise of his explorative tendencies, his aesthetic curiosity, was one of the factors from the very first that gave him a unique evolutionary advantage among other animals. Interaction with materials at this level was both easy and rewarding, and it was probably a necessary preliminary to the selection of the more imaginative and adaptable biological mutants that were to follow. In culture as in biology, man possessed more than the rudiments of technology when he had discovered and prepared his materials for painting and had developed methods of working them with fingertip and brush, crayons, and spray. He also had used specialized tools to sculpt stone and to mold clay at about the same time he learned to finish stone abrasively, and so was freed from dependence on flakeable flint since he could then adapt commoner, harder, polycrystalline rocks such as basalt and granite for his tools.

As in the case of the use of fire by man, the next great innovation in another field of technology, agriculture, was accompanied by a diverse series of auxiliary changes. Man had to develop a whole new set of tools: the hoe to till the ground, the sickle to reap the grain, some kind of flail to thresh the grain, and the quern (mill) to grind it. These tools were made of stone and wood; they were not very efficient. Nevertheless, agriculture was able to provide man with a surer source of food than could be obtained through the older technology of hunting, and it required concomitant advances in materials. Not the least important were fired ceramics which provided the pots needed for cooking, as well as larger containers for rodent-proof storage of crops.

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[12] Cyril Stanley Smith, "Art, Technology, and Science: Notes on Their Historical Interaction," Technology and Culture, 11, 4 (Oct. 1970) 493–549; also published in Perspectives in the History of Science and Technology, Duane H.D.Roller, ed., University of Oklahoma Press, Norman (1971) 129–165.

The introduction of agriculture meant that the supply of animal skins from hunting was diminished, Man had to find substitutes among vegetable fibers, things such as reeds, flax, or cotton, and to utilize the hair of the animals which he had learned to domesticate. Some of these fibers had been used before, especially in woven mats, fences, building components, and basketry, but mainly for clothing. So textiles developed, and textiles inspired new machines: a spinning device (the spindle with its inertia-driven whorl) and a loom for weaving the threads into cloth. The patterns he worked into textiles and painted on his pots gave him practical contact with elements of geometry and with the relationships between short-range symmetry and long-range pattern which reappear in today's structure-based science.

Because the implements and weapons of our prehistoric forebears are crude and primitive in comparison with today's materials and machines, we should not be misled into downgrading the degree of skill which Stone Age man possessed. When, a few years ago, a class at the University of California was provided with a pile of flintstones and given the task of shaping simple stone implements from them, they found that even after many hours of repeated trials, they could not produce a tool that would have sufficed even for a run-of-the-mill Stone Age man.[13] But experience breeds skill, and it is discovery of the possibilities and their interaction with other aspects of culture, not mere duplication, that paces "progress."

The great Neolithic technological revolution—with its development of agriculture and fairly large-scale settled communities—occurred some tens upon tens of thousands of years after man had already mastered his implements of stone and had achieved his intellectual and physical evolution. It set into movement a whole series of technological and cultural changes within the next two millenia which thoroughly transformed man's relations with nature and with his fellow man, and, most important, his thoughts about change and his prospects of the future. While the process might seem slow to us today, it was dynamic by the standards of the preceding ages.

Whether or not the urban society preceded or followed the agricultural revolution, it seems almost certain that the city provided conditions that accelerated man's journey along the path towards civilization; indeed, the two are almost synonymous. During the period from about 5000 to 3000 B.C., two millenia after the introduction of agriculture, a series of basic inventions appeared,[14] Man developed a high-temperature kiln, he learned to smelt and employ metals, and to harness animals. He invented the plow, the wheeled cart, the sailing ship, and writing. Communication and commerce based on specialized skills and localized raw materials both enabled and depended upon central government together with reinforcing religious, social, and scientific concepts. The great empires in Mesopotamia and Egypt, the

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[13] Walter Sullivan, "Anthropologists Urged to Study Existing Stone-Age Cultures," New York Times (April 5, 1965). (Description of conference paper by John Desmond Clark, University of California-Berkeley)

[14] V.Gordon Childe, What Happened in History, Penguin edn., New York (1946).

forerunners of our Western civilization, were based on the interaction of many institutions and ideas, but materials were necessary for them to become effective. Indeed, the characteristics of this early period are mainly an interplay between principles of human organization and the discovery of the properties of matter as they resided in a wide diversity of materials. Both tools and buildings were simple; mechanisms comparable in ingenuity to the materials used in the decorative arts of Sumer, Egypt, and Greece do not appear until much latter. All, as far as we can tell, were based on experience and empiricism with little help from theory.

BRONZE AND IRON AGES

Stone was eventually supplemented by copper, and copper led to bronze. Near the end of the period under discussion, bronze in turn was partially displaced by iron. So important is the change in materials base of a civilization that the materials themselves have given rise to the names of the ages—the Stone Age, the Bronze Age, and the Iron Age. In the 19th century after much groundwork both literally and figuratively by geologists, paleontologists, and archeolegists, these terms came to supersede both the poets gold and silver ages and the philosopher's division of the past into periods based on religious, political, or cultural characteristics.[15]

There were no sharp chronological breaking points between the three ages, nor did the switch from one material to another take place everywhere at the same time. Even, for example, in those areas where bronze tools and weapons came into use, stone tools and weapons remained on the scene for a long time. Similarly, iron did not Immediately replace bronze, and indeed, there were still some civilizations which passed directly from stone to iron and some which, from indifference or from lack of knowledge, never adopted either metal. As a matter of fact, the first tools and weapons of iron were probably inferior to the contemporary bronze tools whose technology had been known for over two millennia. At first, the advantage of iron over bronze was based on economics, not superior quality. Iron was laborious to melt, but it could be made from widespread common minerals. A monarch could arm his entire army with iron swords, instead of just a few soldiers with bronze swords when the rest would have to fight with sticks and bows and arrows. With iron came a quantitative factor that had profound social, economic, and political consequences for all aspects of culture.[16]

Native metals, like gold, silver, and copper, were hammered into decorative objects during the 8th millennium B.C. in an area stretching from Anatolia to the edge of Iran's central desert, during the 5th millennium B.C. in the Lake Superior region of North America, and during the mid-2nd millennium B.C. in South America. However, it was not until man learned to smelt

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[15] Robert F.Heizer, "The Background of Thomson's Three-Age System," Technology and Culture, 3 (Summer 1962) 259–266.

[16] Leslie Aitchison, A History of Metals, 2 volumes, Macdonald and Evans, London (1960); Interscience Publishers, New York (1960) provides the background for much of the discussion of metals that follows. See also Theodore A.Wertime, "Man's First Encounters with Metallurgy," Science, 146, no. 3649 (December 4, 1964) 1257–67.

metals and reduce them from their ores, to melt and cast them, that metallurgy proper can be said to have begun. Again, the early advantage was only an economic one, the mineral ores of copper being vastly more abundant than is the native metal, but the way was opened for alloying and the discovery of entirely unsuspected properties. Moreover, with molten metal, casting into complicated shapes became possible,

The discovery of smelting has left no records, Given the availability of adequately high-temperatures in pottery kilns and the use of metal oxides for decoration, drops of reduced metal could well have been produced repeatedly before the significance was grasped. But once it was, empirical experiments with manipulation of the fire and the selection of the appropriate heavy, colored minerals would have given the desired materials with reasonable efficiency. A kiln works best with a long-flame fuel such as wood; smelting is best done with charcoal and with a blast from a plowpipe or bellows, but the time when these were first used has yet to be established. The first alloys were probably made accidentally in the smelting of a copper ore containing arsenic and/or antimony, which improve both the castability and the hardness without undue loss of the essential metallic property of malleability. For a thousand years, these alloys were exploited, until finally they were largely replaced by bronze, an alloy made from a heavy readily identifiable, though scarce, mineral, and having somewhat superior properties to those of the copper-arsenic alloys; there was also the added advantage that those who knew how to use it lived longer!

A lively argument is currently going on among archeologists as to whether the original discovery of bronze took place in the region of Anatolia and the adjacent countries to the South and East or in Eastern Europe—or independently in both.[17] Whatever the evolutionary process of the development of metallurgy, there is no doubt that it had profound social, economic, and political consequences.

Though the earliest stone industry and commerce had required some organized system of production, and division of labor was well advanced in connection with large irrigation and building projects,[18] the use of metals fostered a higher degree of specialization and diversity of skills; it also required communication and coordination to a degree previously unknown. Both trade and transportation owe much of their development to the requirements of materials technology: not only ores, requiring bulk transportation over great distances from foreign lands, but also precious objects for the luxury trade, such as amber, gem stones, gold and silver jewelry, fine decorated ceramics, and eventually glass.

The search for ways of working materials prompted man's first use of machines to guide the power of his muscles. Rotary motion had many applications that were more influential than the well-known cartwheel. Perhaps

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[17] Colin Renfrew, "The Autonomy of the East European Copper Age," Proceedings Prehistoric Society, 35 (1969) 12–47.

[18] Karl A.Wittvogel, Oriental Despotism, Yale University Press, New Haven (1957).

beginning with the child's spinning top, it was the basis of many devices, the most important of which were the drill for bead-making, stone-working, and seal-cutting; the thread-maker's spindle; the quern; and above all, the potter's wheel.[19] These provided the foundation for the earliest mechanized industries, and were steps toward the mass-production factories of the 20th century.

Materials development had an impact on culture in other ways than through the improvement of artifacts. This can perhaps best be seen in the development of writing. The growth of commerce and government stimulated the need for records. The materials to produce the records undoubtedly influenced the nature of the writing itself and, if modern linguistic scholars are correct, probably some details of the language structure and hence the mode of thought. Marshall McLuhan has popularized the phrase, "the medium is the message." A painting, a poem, a print, a pot, a line of type, a ballet, a piece of carved sculpture, a hammered goldsmith's work, or a TV image, all convey differences in sensory perceptions which form the basis of human communication,[20] and we might guess that the same process occurred at the very beginning of art and purposeful records. The Sumerians in the Tigris-Euphrates valley had abundant clay to serve as their stationery, and the sharp stylus employed with it did not allow a cursive writing to develop; did this have some impact on the ways in which they thought, spoke, and acted? The Egyptions, on the other hand, could adapt the interwoven fibers of a reed growing in the Nile delta to produce a more flexible medium, papyrus, on which they could write with brushes and ink in less restricted ways. Thus, the differences between the cuneiform and hieroglyphic writing were dependent on the differences in materials available, quite as much as were the mud-brick and stone architecture of their respective regions. At the time, the visual arts were probably more significant than writing, for relatively few people, except professional scribes, would have been influenced by the latter. Certainly, our retrospective view of old civilizations depends on the preservation of art in material form, and the material embodiment of thought and symbol in the visual environment must have modified the experience and behavior of ancient peoples, even as it does today.

The replacement of copper and bronze by iron began about 1200 B.C. Iron had been produced long before then, because iron ores are prevalent and easily reduced at temperatures comparable to those required for smelting copper. However, the iron was probably not recognized as such, because at those temperatures it is not melted, but remains as a loose sponge of particles surrounded by slag and ash, being easily crumbled or pulverized and having no obvious metallic properties. If, on the other hand, the porous mass is hammered vigorously while hot, the particles weld together, the slag is forced out, and bars of wrought iron are produced.

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[19] V.Gordon Childe, "Rotary Motion," A History of Technology, I, Charles Singer et al., eds., Oxford University Press, New York and London (1954), chap. 1.

[20] Marshall McLuhan, Understanding Media: The Extensions of Man, McGraw-Hill, New York (1964).

Though metallic iron may have been previously seen as occasional lumpy by-products from lead and copper smelting (in which iron oxides were used to make siliceous impurities in the iron more fusible), its intentional smelting is commonly attributed to the Hittites, an Anatolian people, about 1500 B.C. The Hittite monopoly of ferrous knowledge was dispersed with the empire about 1200 B.C., but it took almost another 500 years before iron came into general use and displaced the mature metallurgy of bronze. Immense skill was needed to remove the oxygen in the ore by reaction with the charcoal fuel without allowing subsequent absorption of carbon to a point where the reduced metal became brittle. Moreover, each ore had its own problems with metalloid and rocky impurities.[21]

Certain forms of iron—those to which the name steel was once limited—can become intensely hard when heated red hot and quenched in water. This truly marvelous transmutation of properties must have been observed quite early, but its significance would have been hard to grasp and, in any case, it could not be put to use until some means of controlling the carbon content had been developed. Since the presence of carbon as the essential prerequisite was not known until the end of the 18th century A.D., good results were achieved only by a slowly-learned empirical rule-of-thumb schedule of the entire furnace regimen. Even the process of partial softening, today called tempering, was very late in appearing (perhaps in the 16th century) and early "tempering" was actually hardening done in a single quenching operation, in which the steel was withdrawn from the cooling bath at precisely the right moment. It is not surprising that this was rarely successful. Yet, even without hardening, iron had no difficulty in supplanting bronze for many applications. Its abundance meant that the elite could not control it. Iron was the "democratic" metal because a rise in the living standards among larger masses of population was obtainable through its application in tools and implements.[22]

The wide distribution of iron over the earth's surface enabled it to serve for tools and agricultural implements as well as weapons of war and precious objects for the ruling households. Before 1,000 B.C., there are records of iron hoes, plowshares, sickles, and knives in use in Palestine. From about 700 B.C., iron axes came into play for clearing forest land in Europe and for agricultural purposes. Iron tools together with evolving organization arrangements greatly increased the productivity of agriculture, giving a surplus which could support large numbers of specialized craftsmen whose products, in turn, could become generally available instead of being monopolized by the wealthiest ruling circles. Furthermore, tools formerly made of bronze or stone—such as adzes, axes, chisels, drills, hammers, gravers, saws, gauges—could be made less expensively and more satisfactorily in iron. The new tools allowed for new methods of working materials: forging in dies, the stamping and punching of coins, and, many years later, developments such as the drawing of wire and the rolling of sheet and rod.

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[21] R.J.Forbes, "Extracting, Smelting, and Alloying," A History of Technology I, Charles Singer et al., eds, chap. 21 (see reference 19).

[22] Samuel Lilley, Men, Machines and History, International Publishers, New York (1966) 9–12.

These metalworking methods were easily harnessed to water power when it appeared and opened up ways of making more serviceable and cheaper products. Though it was not immediately exploited, the strength of metals permitted the construction of delicate machines. Iron was at first used structurally only for reinforcing joints in stone or wood, but later its strength and stability were combined with precision in creating the modern machine tool, and its large-scale fabrication also made modern architecture possible.

MATERIALS IN CLASSICAL CIVILIZATION

It has been claimed that bronze made for the centralization of economic power as well as the concentration of political authority in the hands of an aristocratic few, while iron broadened the economic strength to a larger class of traders and craftsmen and so led to the decentralization of power and eventually to the formation of Athenian democracy.

Although the classical civilization of Greece rather fully exploited the possibilities offered by metals and other materials available to them from preceding ages, producing beautifully-wrought ceramics, exquisite jewelry, superb sculpture, and an architecture which still represents one of the peaks of the Western cultural and aesthetic tradition, they did little to innovate in the field of materials themselves.

The same is true of the Romans who acquired a great reputation as engineers, and rightly so, but this rests largely upon the monumental scale of their engineering endeavors—the great roads, aqueducts, and public structures—rather than upon any great mechanical innovations or the discovery of new materials.

There is one exception to this generalization. The Romans did introduce a new building material: hydraulic concrete. The use of lime mortar is extremely old, probably even preceding the firing of pottery, and lime plaster was used for floor and wall covering, for minor works of art and later for the lining of water reservoirs and channels. It can be made by firing limestone at a moderate red heat; it sets hard when mixed with water and allowed slowly to react with carbon dioxide in the air. If, however, the limestone contains alumina and silica (geologically from clay) and is fired at a higher temperature, a material of the class later to be called hydraulic, or Portland, cement is formed. After grinding and mixing with water, this sets by the crystallization of hydrated silicates even when air is excluded and develops high strength. The Romans were fortunate in having available large quantities of volcanic ash, pozzuolana, which, when mixed with lime, gave such a cement. They exploited it to extremely good purpose (reinforced with stone rubble or with hard bricks) in the construction of buildings, bridges, and aqueducts. Massive foundations and columns were much more easily built than with the older fitted-stone construction, and, unlike mortar, the cement was waterproof. By combining the new cement with the structural device of the arch, the Romans could roof-over large areas without the obstructions of columns.[23]

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[23] Norman Davey, A History of Building Materials, Phoenix House, London (1961).

The case of hydraulic cement is representative of materials usage from antiquity until modern times. Namely, it was developed entirely on an empirical basis, without much in way of any science underlying the useful properties. The great Greek philosophers, to be sure, had worried about the nature of matter and the three states in which it exists—solid, liquid, and gas. These, indeed, constitute three of the four famous elements of Aristotle which dominated philosophy for nearly 2000 years. His earth, water, and air represent fine physical insight, but they had to be rejected by chemists in their search for compositional elements.[24] But in any case, it was not philosophy that guided advance. The main contribution to early understanding came from the more intelligent empirical workers who discovered new materials, new reactions, and new types of behavior among the grand diversity of substances whose properties could be reproduced, but not explained except on an ad hoc basis. Through most of history, it has been the almost sensual experience with that complex aggregation of properties summed up in the term the "nature" of the material that has guided empirical search for new materials and modifications of old ones. The ability to go beyond such empiricism and to plan tests on the basis of an adequate theory of the composition-structure-property" relationships is a 20th century phenomenon and had to await the development of science. Moreover, the science needed was a kind that was slow to emerge because of the extreme complexity of the problems involved.

Unlike astronomy, there was little place for accurate measurements or geometry in materials, and those who sought to find rules were perpetually frustrated. The curious experimenter, however, by mixing, heating, and working materials in a myriad of ways did uncover virtually all of the materials with properties that were significant to him, namely, strength, malleability, corrosion resistance, color, texture, and fusibility. Science began to be helpful much later when chemical analysis—an outgrowth of the metallurgists' methods of testing the metal content in ores before going to full-scale operation—advanced to the point where it showed that there were only a limited number of chemical elements and that ostensibly similar materials, differing in their nature, often contained different impurities. Then it was discovered that chemical substances of identical composition could differ in their internal structure, and finally structure became relatable to properties in a definite way; in fact, it was found possible to modify the structure purposefully to achieve a desired effect.[25]

There have been many interpretations of the decline and fall of the Great Roman Empire. The early Christian apologists claimed that Rome fell because it was wicked and immoral; in the 18th century, Gibbon blamed the fall of Rome upon Christianity itself. Since that time, the "fall" has been attributed to numerous factors: political, economic, military, cultural, and the like. It is not surprising, with the recent interest in the history of technology, that technological interpretations of Rome's decline have begun to appear, and some

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[24] C.S.Smith, "Matter vs. Materials: A Historical View," Science, 162 (1968) 637–644,

[25] C.S.Smith, A History of Metallography, University of Chicago Press, (1960); Chicago (1960); idem, "Metallurgy as a Human Experience," Metallurgical Transactions 6A (1975) 603.

of these center on Rome's use of materials, A few years ago, S.C.Gilfillan claimed that the decline of Rome was due to a decline in the birth rate of the Roman patrician class coming from dysgenic lead poisoning.[26] Although all Romans got a goodly intake from their lead-lined water system, the elite drank more than its share of wine from lead vessels and this was thought to reduce the fertility of the leaders! Lately, a geochemist has claimed that Rome's troubles derived from the economic effects of the enforced decline in silver production which began about 200 A.D. because the mines had become so deep that they could no longer be cleared of water with the technical means available.[27]

MEDIEVAL MATERIALS

Throughout the first millennium after Christ, about the only places where ancient techniques of making and working materials underwent improvement were outside Europe—in the Arab World, Iran, India, and the Far East. Textiles, ceramics, articles in silver and bronze and iron of excellent quality appeared. That portentous new material, paper, originated in China and began its Western diffusion. Though the armorers of the Western world were steadily enhancing their products, the Crusaders of the 12th century had no steel which could match that of the Saracen sword. The Japanese sword surpassed the Islamic one by an even greater margin than the latter did the European. However, not for several centuries did these Oriental priorities in materials processing have any effect upon the materials science or technology of contemporary Western Christendom.

For all this, the first significant literature on materials is European—the Treatise on Divers Arts written about 1123, by a Benedictine monk under the pseudonym Theophilus.[28] He was a practical metalworker and he described in full practical detail all the arts necessary for the embellishment of the church, such as the making of chalices, stained-glass windows, bells, organs, painted panels, and illuminated manuscripts.

Theophilus was no materials engineer in the modern sense, but he was a craftsman, probably, the historical goldsmith Roger of Helmarshausen, some of whose work has survived. His knowledge of matter was the directly-sensed, intuitive understanding that comes from constantly handling a wide variety of substances under different conditions. His Treatise is essentially a factual

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[26] S.C.Gilfallan, "Roman Culture and Dysgenic Lead Poisoning," The Mankind Quarterly, V, 3 (January-March 1965) 3–20; see also Gilfillan, "The Inventive Lag in Classical Mediterranean Society," Technology and Culture, 3, (1962) 85–87.

[27] C.C.Patterson, "Silver Stocks and Their Half-Lives in Ancient and Medieval Times," Economic History Review (1972).

[28] There have been two recent English translations of Theophilus: C.R.Dodwell, Thomas Nelson and Sons, London (1961), and Cyril Stanley Smith and John G. Hawthorne, University of Chicago Press, Chicago (1963). For a further discussion, see Lynn White, Jr., "Theophilus Redivivus," Technology and Culture, 5 (1964) 224–233.

"how-to" book, containing many exhortations to watch carefully for subtle changes in the materials being processed but with no trace of theoretical explanation. Theory does not appear in treatises intended to help the practical worker in materials until 600 years later—well into the 18th century.

Although the nature of materials themselves did not change greatly in Western Europe during the Middle Ages, a number of mechanical inventions facilitated both their production and their shaping.[29] The first widespread application of power in processing materials was in grinding grain. This practice considerably increased when windpower supplemented the older waterpower, with the technique, as so much else, diffusing from the East. Textiles at first benefited only by the use of waterpower in the fulling process, but the mechanically simpler and more laborious metallurgical processes changed substantially. In ironworking, waterpower was applied successively to bellows, to hammers, and eventually (15th century) to slitting, rolling, and wire drawing.

A series of mechanical innovations and improvements led to advances in the manufacturing and processing of other materials, too. Plant ash to make glass was replaced by more-or-less pure soda, and the furnaces to melt it in became larger. Textile looms improved, especially with the introduction—from China—of the draw loom. Even more important was the development, near the close of the 13th century, of the spinning wheel, in place of the ancient handspun whorl, virtually unchanged since prehistoric times.

Power not only enabled the scale of operation to be increased in ironworking, but the product was more uniform because of the extensive working that was possible. In addition, the use of power changed the basic chemistry of the process. Although a large furnace is not needed in order to produce molten cast iron, it is much more easily made in a tall shaft furnace driven by powerful bellows than in a low hearth. Cast iron first appeared in Europe in the 14th century, following a sequence of developments which is unclear but which certainly involved power-driven bellows, larger furnaces, and perhaps hints from the East. To begin with, cast iron was used only as an intermediate stage in the making of steel or wrought iron, and it was developed for its efficiency in separating iron from the ore by production of liquid metal and slag. However, cast iron that contains enough carbon to be fusible is brittle, and it took Europeans some time to realize its utility, although it had long been used in the Far East.

By the beginning of the 15th century, cast iron containing about 3% carbon and commonly about 1% silicon and which melts at a temperature of about 1200° C in comparison with 1540° C for pure iron, had found three distinct uses—as a bath in which to immerse wrought iron in order to convert it into steel as a material to be cast in molds to produce objects like pots, fire irons, and fire backs more cheaply; and, most important of all, as the raw material for the next stage of iron manufacture.

The age-old process of directly smelting the ore with charcoal and flux

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[29] Lynn White., Jr., Medieval Technology and Social Change, Clarendon Press, Oxford (1962),

in an open hearth or low shaft furnace yielded a product of low-carbon material in the form of an unmelted spongy mass, which was forged to expel slag, to consolidate it, and shape it. It was inefficient because of the large amount of iron that remained in the slag, and the iron was defective because of the slag remaining in it. The wrought iron produced from cast iron by the new finery process was made by oxidizing the carbon and silicon in cast iron instead of by the direct reduction of the iron oxide ore. The two-stage indirect process gradually displaced the direct method in all technologically advanced countries. Its main justification was economic efficiency, for the resulting product was still wrought iron or steel, finished below its melting point and containing many internal inclusions of iron-silicate slag. In the late 18th century, the small hearth was replaced by a reverberatory puddling furnace which gave much larger output, but neither the chemistry nor the product was significantly different from that of the early finery.[30]

It was only with the possibility of obtaining temperatures high enough to melt low-carbon iron—essentially the time of Bessemer and Siemens in the 1860's—that slag-free ductile iron became commercially possible. The very meaning of the word “steel” was changed in the process, for the word, previously restricted to quench-hardenable Medium- and high-carbon steel for tools, was appropriated by salesmen of the new product because of its implication of superiority.

The early developments in iron and steel metallurgy occurred with no assistance from theory, which, such as it was, was far behind practice. Medieval alchemists were not experimenting with cast iron because they felt they understood its chemistry, and they had not thought of its many potential uses.

The Aristotelean theory of matter, essentially unchallenged in Medieval times, recognized the solid, liquid, and gaseous states of matter in three of the four elements—the earth, water, air, and fire. The theory encompassed the various properties of materials but was wrong in attributing their origin to the combination of qualities rather than things. Medieval alchemists in their search for a relation between the qualities of matter and the principles of the universe elaborated this theory considerably. One of their goals—transmutation—was to change the association of qualities in natural bodies. In the days before the chemical elements had been identified, this was a perfectly sensible aim. What more proof of the validity of transmutation does one need than the change in quality of steel reproducibly accomplished by fire and water? Or the transmutation of ash and sand into a brilliant glass gem, and mud into a glorious Attic vase or Sung celadon pot? Or the conversion of copper into golden brass? Of course, today we know that it is impossible to duplicate simultaneously all the properties of gold in the absence of atomic nuclei having a positive charge 79. One way to secure a desired property is still to select the chemical entities involved but much can also be done by changing the structure of the substance. Modern alchemy is as much solid-state physics as it is chemistry, but it could not have appeared until chemists had unraveled the nature and number of the elements.

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[30] H.R.Schubert, History of the British Iron and Steel Industry…to AD 1775, London (1957).

Urged on by the manifestly great changes of properties accompanying chemical operations, the alchemists worked on the same things that concerned the practical metallurgist, potter, and dyer of their day, but the two groups interacted not at all. In retrospect one can see that the alchemist's concern with properties was not far from the motivation of the present-day materials scientist and engineer. They were right in believing that the property changes accompanying transmutation were manifestations of the primary principles of the universe, but they missed the significance of the underlying structure. Moreover, they overvalued a theory that was too ambitious, and so their literature is now of more value to students of psychology, mysticism, and art than it is a direct forerunner of modern science. Yet the alchemists discovered some important substances; they developed chemical apparatus and processes which are basic to science today, and they represented an important tradition of the theoretically-motivated experimentation, even if they failed to correct their theory by the results of well-planned critical experiments.[31] This approach proved sterile during the Middle Ages, while the workshop tradition represented by Theophilus led to many advances. The collaboration between the two approaches, which is the very basis and principal characteristic of today's emerging MSE was then impossible.

Two major technological developments helped precipitate the changes that signalized the close of the Middle Ages and the beginning of modern times: gun powder and printing. Both of these had earlier roots in Chinese technology and both were intimately related to materials.

In the case of printing,[32] all the necessary separate elements were in general use in Western Europe by the middle of the 15th century; paper, presses, ink and, if not moveable type, at least wood-block printing of designs on textiles and pictures and text on paper, and separate punches to impress letters and words on coins and other metalwork. But, they had not been put together in Europe. Papyrus and parchment had been known in ancient times. Paper made of vegetable fiber had been invented in China a thousand years earlier and had been introduced into Spain by the Arabs during the 12th century. Simple presses were already in use for making wine and oil, while oil-based ink (another essential element in the printing process) had been developed by artists a short time previously.

The idea for the most important element needed for mass production of verbal communication—reusable individual type—probably came to Europe from the Orient, although the history is obscure. By the 11th century, Chinese printers were working with baked ceramic type mounted on a backing plate with an adhesive and removable for reuse. By the 14th century, in Korea, even

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[31] R.P.Multhauf, The Origins of Chemistry, Oldbourne, London (1966) provides an authoritative and lucid discussion of the development of chemical theory and practice and their relations to materials.

[32] The standard work on the history of printing is: Thomas F.Carter, The Invention of Printing and Its Spread Westward, revised by L.Carrington Goodrich, 2nd ed., Ronald Press, New York (1955). See also H.Carter, A View of Early Typography, Oxford University Press, Oxford (1969).

cast bronze type was known.

Shortly after 1440 in Europe, everything came together in an environment so receptive that the development was amost explosive. Though there may have been experiments in the Lowlands, the successful combination of all the factors occurred in Mainz in Germany, where Johann Gutenberg began experiments in the casting of metal type during the 1440's. By 1455 he and his associates were able to produce a magnificent book, the "Gutenberg Bible," still one of the finest examples of European printing. It consists of 643 leaves, about 40 × 29 cm in size, printed on both sides with gothic type in two columns. Some chapter headings were printed in red, others inserted by hand. Part of the edition was printed on paper, part on vellum, the traditional material for permanence or prestige. Unlike the earlier Oriental type, Gutenberg's was cast in a metal mold having a replacable matrix with a stamped impression of the letter, arranged so that the body of the type was exactly rectangular and would lock firmly together line-by-line within the form for each page. Both the metal and the mold were adopted from the pewterer's practice. Thus, a new technique for mass production and communication was established, ushering in a potential instrument for mass education. Modern times were beginning.

The political and economic environment had been strongly influenced somewhat earlier by the introduction of gunpowder in Western Europe. Explosive mixtures for holiday firecrackers had been used for centuries in China; it was only in the "civilized" West that gunpowder was first employed to enable man to kill his fellowman. Here, too, it is uncertain whether introduction of gunpowder in the West was a result of independent discovery or diffusion from the Far East. At any rate, the application and development was different and prompt. As early as 1325, primitive cannon were built in the West for throwing darts, arrows, and heavy stone balls, in competition with the mechanical artillery (the ballista) familiar since the days of the Romans, which were displaced completely by the middle of the 16th century. By 1450, the musket had appeared, and began to render the cross-bow and long-bow obsolete.

By 1500, bombards, mortars, and explosive mines caused the medieval elements of warfare—the fortified castle and the individual armored knight—to lose their military importance, and contributed to the decline of the feudal nobility.[33] (Another technical device—the stirrup, had aided their rise.)[34] Accordingly, the changes in the technology of warfare aided in the process of administrative and territorial consolidation which was to give birth to the national state and transform the map of Europe.

Even the layout of cities changed as a result of the new methods of warfare: the round towers and high straight walls no longer afforded good defense in the age of cannon; they were replaced by geometrically-planned walls and arranged so that every face could be enfiladed.

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[33] A.Rupert Hall, "Science, Technology, and Warfare, 1400–1700," Science, Technology, and Warfare, Monte D.Wright and Lawrence J.Paszk, eds., Office of Air Force History and United States Air Force Academy, U.S. Government Printing Office, Washington, D.C. (1970) 3–24.

[34] Lynn White, Jr. (Reference 29, page 1–19) 3–24.

Military needs sparked a great development in the scale of the material-producing industries during the Renaissance, but agriculture, construction, and the generally rising standard of living also contributed and benefited. The new supply of silver coming from Spanish operations in the New World and, no less, from the development of the liquation process for recovering silver from copper upset the monetary balance of Europe. Silver, pewter, wood, and the greatly-increased production of glazed ceramic vied with each other for domestic attention, and glass democratically appeared in more windows and on more tables.

We know much more about material-producing processes in the 16th century than we do of earler ages, because the printing press gave a wider audience and made it worthwhile for men to write down the details of their craft in order to instruct others rather than to keep their trade secrets. Some of our most famous treatises on materials technology date from the 16th century, and the best of these continued to be reprinted over 150 years later—an indication that practices were not advancing rapidly.

The most famous of these treatises is the de Re Metallica[35] by Georg Bauer (Latin, Georgius Agricola) published posthumously in 1556. Agricola was a highly literate and intellectually curious physician living in Bohemian Joachimstal and Silesian Chemnitz, both mining and smelting towns, and his systematic factual descriptions of minerals, mining, and smelting operations, all excellently illustrated, shed much light on the devices and techniques of the times. Agricola writes of large-scale industrial operations, with a center of interest far removed from the craftsman's workship by Theophilus centuries earlier. The scale is that of a capitalistic enterprise. Nevertheless, Agricola still thought in the same terms as did Theophilus; his de Re Metallica is simply a description of actual practice, devoid of any theoretical principles, though in other works he did speculate fruitfully on the nature and origin of minerals.

Sixteen years earlier, the Italian foundryman Vannoccio Biringuccio had published his de 1a Pirotechnia, which is much broader in scope.[36] It has less detail on the smelting operations, but is excellent on all aspects of casting and working metals and has good discussions of glassmaking, smithy operations, the casting of bells, and especially the manufacture of cannon and gunpowder. He says that the bronze founder looks like a chimney sweep, is in perpetual danger of a fatal accident and fearful of the outcome of each casting, is regarded as a fool by his countryment, "but with all this it is a profitable and skilled art and in large part delightful." Biringuccio says that fortune will favor you if you take proper precautions in doing your work in the foundry, and he advocates the empirical approach, almost as a modern experimentalist, in these words, "It is necessary to find the true method by doing it again and again, always varying the procedure and then stopping at the best." His section on casting, boring, and mounting of cannon is specially good, and shows

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[35] An English translation of Agricola was published by Herbert C.Hoover and his wife Lou Henry Hoover, London (1912); reprinted by Dover, New York (1950). See also Bern Dibner, Agricola on Metals, Burndy Library, Norwalk, Connecticut (1958

[36] C.S.Smith and M.T.Gnudi, The Pirotechnia of Vannoccio Biringuccio, AIME, New York (1942); paperbound edition, MIT Press, Cambridge, Mass. (1966)

how dependent all this was on the earlier technique of the bell founder, which he also meticulously reports.

Both Agricola and Biringuccio describe the quantitative analytical methods for assaying ores and metallurgical products. Even better on this aspect of chemistry is the great treatise of Lazarus Ercker, the Beschreibung allerfürnemisten mineralischen Ertzt und Bergwercksarten, published in Prague in 1574.[37] Ercker's exposition of the assayer's art displays intimate knowledge of the reactions, miscibilities, and separations of the common metals and oxides, sulfides, slags, and fluxes as well as sophisticated methods of cupelling, parting with acid, etc., and is thoroughly quantitative in outlook and intent.

In all these early writings, there is a strong bias toward the precious metals, gold and silver. Even Biringuccio, who was concerned with end-use far more than other writers, had very little to say about iron despite the fact that this was the most common metal then, as now. The rough labor of the smith was almost beneath the notice of educated men. There is no comprehensive book devoted to iron until that of R.A.F.de Réaumur published in 1722.[38] This was preceded only by an anonymous little treatise on the hardening and etching of iron (1532), a Polish poem of 1612 (The Officina Ferraria by W.Rozdienski) and a fine description of locksmiths' and skilled ironworkers' operations by Mathurin Jouse in 1627.[39] Though glass is treated in fair detail by Biringuccio, the first book devoted entirely to it is that by Neri in 1612.

Other practical arts gradually received a place in the visible literature. Piccolpasso's unpublished manuscript of 1550 has fine detail on all stages of ceramic manufacture, glazing, and decoration.[40] The Plictho of Fioventura Rosetti (1548) has descriptions on dyeing.[41] Other booklets give innumerable recipes for the making of ink, soldering, gilding, removing spots, along with many cosmetic and household craft recipes.[42] The sudden appearance of this literature in print does not mean that the processes described were new in the 16th century; indeed, most of them had been going around for centuries, circulated by word-of-mouth or in rough manuscripts of a form and content that no literary custodian would think worth keeping.

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[37] A.G.Sisco and C.S.Smith, Lazarus Ercker's Treatise on Ores and Assaying, University of Chicago Press, Chicago, Illinois (1951).

[38] R.A.F.de Réaumur, Memoirs on Steel and Iron, translated and edited by A.G.Sisco, University of Chicago Press, Chicago, Illinois (1956).

[39] Cyril Stanley Smith, ed., Sources for the History of Science and Steel, 1532–1786, MIT Press, Cambridge, Mass. (1968).

[40] Cipriano Piccolpasso, The Three Books of the Potter's Art, edited and translated by B.Racham and A.van de Put, London (1934).

[41] Sidney M.Edelstein and Hector Borghetty, eds., The Plictho of Gioanventura Rosetti, MIT Press, Cambridge, Mass. (1969).

[42] For a bibliography and analysis of these works, see James Ferguson, "Some Early Treatises of Technological Chemistry," Proc. Philosophical Society, Glascow; 1888 19, 126–59; 1894, 25, 224–35; 1911, 43, 232–58; 1912, 44, 149–89.

If in this treatment we seem to have overemphasized the 16th century, it is because intimate records become available for the first time of techniques built upon many centuries of slow consolidation of changes. These writings show vividly how much can be done without the benefit of science, but at their own times they served to disseminate to a large and new audience knowledge of the way materials behaved; such knowledge was an essential basis for later scientific attack.

With the exception of Agricola, all of this literature was written in the vernacular tongue, Italian, French, or German. It was part of the Reformation. Instead of theoretical dogma handed down from on high for intellectual gratification, it was down-to-earth practical information for the workshop and kitchen. The realization that theory could help this kind of practice was quite slow in emerging, and a real science of materials had to wait for another two centuries. In the meantime, the separate components of ferrous and nonferrous metallurgy, ceramics, dyeing, fiber technology, organic polymers, and structural engineering pursued their own separate lines of development, and the basic sciences of chemistry and physics slowly generated an understanding that would help explain practice, enrich, and extend it. Together, this all served to provide the facts and viewpoints that would eventually knit into the new grouping of man's knowledge and activity known as materials science and engineering.

THE START OF A SCIENTIFIC MATERIALS TECHNOLOGY BASED ON CHEMISTRY

The linking of theoretical understanding with practical applications, the hallmark of MSE, did not occur with the Scientific Revolution of the 17th century nor the Industrial Revolution of the 18th and 19th centuries. Tremendous advances occurred during the 17th to 19th centuries in scientific understanding of the nature and operation of the physical universe at both atomic and cosmic levels, but very little of this could find direct connection to the materials made and used by man. Although major transformations were taking place in the processing and application of old materials, and new ones were being developed, these were largely the product of empirical advances within materials technology itself, owing little to contemporary scientific understanding.

Indeed, the very complicated origins of the useful properties of materials precluded understanding by the necessarily simplistic methods of rigorous science. Though kinetics and elasticity were simple enough to be handled by the new mathematics, the mechanics of plasticity and fracture were utterly beyond it. Unsuspected variations in composition and structure produced changes in properties that could be manipulated only by those who enjoyed messy reality. Science could advance only by ignoring these problems and finding others in which it was possible, both theoretically and experimentally, to exclude unknown, unwanted, or uncontrollable variables.

Eventually, of course, on the fragmentary knowledge so acquired, it became possible to deal with real materials, but those properties that are structure-sensitive—which includes most of the interesting properties of matter from the user's viewpoint—have been very late in succumbing. It would surely have delayed understanding had some superpower insisted that physicists work upon important but insolvable (at that time) properties of matter. Materials practitioners cannot disregard those aspects of the behavior of matter simply because a scientist cannot deal with them. The development of the different threads of knowledge proceeds each at its own pace. Every scientific concept has come about from an analytical understanding of only a part, albeit often the central part, of a real complex phenomenon. The approach usually requires a temporary blindness to some aspect of the rich behavior of nature, which stimulated the study in the beginning. A price is paid for each step in understanding. Eventually, however, the excluded aspects, at least if they are real, can be included in a higher synthesis. However, the history of MSE shows that this synthesis is more than the putting together of exact understanding of many parts; it is putting this understanding into a higher, or at least broader, framework which combines experience as well as logic. All levels, all viewpoints must interact and the present tension between the different parts of the materials profession gives ground for hope that new methods of managing this difficult synthesis are beginning to emerge. It is rare for both attitudes of mind to be combined in one individual, but a tolerance indeed an enjoyment, of opposing points-of-view is one of the things that makes MSE so interesting today.

In the past, even when breakthroughs occurred which might have illumined the nature and structure of materials, their significance was not immediately apparent to the practitioner and the impact on technology was delayed. With only a few exceptions, the coupling of science to engineering had to await the slow development of new concepts, a tolerance for new approaches, and the establishment of new institutions to create a hybrid form: engineering science, or, if one prefers, scientific technology—which is basically different from both the older handbook-using technology and rigorous exclusive science.[43] This is mainly a 20th-century, even a mid-20th-century, development.

With hindsight, we can see how scientific advances of earlier times could have been adopted by contemporary engineers more promptly than they actually were. Nevertheless, a practical metallurgist or potter quite rightly disregarded the theoretical chemistry of 1600 A.D. as well as the physicist's ideas on matter in 1900 A.D. Both would have been quite useless to him. Yet, with the passing of time, these inapplicable approaches developed to the point where many new advances stemmed from them. We can equally wonder why scientists were frequently so obtuse as to make no attempt to investigate or to comprehend the fascinating complex problems which arose in practice. Such an approach would have been completely a-historical. It would ignore the fact that the implications of new viewpoints tend not to be apparent to men whose practice and whose ideas are in productive harmony at the time; it would also ignore the fact that science and technology had developed out of different traditions—the philosophic and scholarly on one hand, the art and craft and oral tradition on the other. A major reshuffling of attitudes and institutional devices was essential before the two could be brought together in a

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[43] Edwin Layton, "Mirror-Image Twins: The Communities of Science and Technology in 19th-century America," Technology and Culture, 12 (Oct. 1971), 562–80.

fruitful relationship; what is more, science and technology had to advance, each in its own way, to the point where they addressed themselves to common problems.

Science arose from a kind of union between philosophy and technology, but it was only when both science and technology had each reached a high level of development that continued progress became difficult without concomitant advances in the other. It was then recognized that their unified actions were mutually beneficial, and of service to mankind.

If we outline briefly the developments in materials science and in materials engineering during the 18th and 19th centuries, we can see some hints of the eventual emergence of the new and fruitful relationship to which we have given the name of "scientific technology."

The story of sal ammoniac in the 18th century is instructive in this regard. Robert T.Multhauf has shown how virtually all of the chemical data needed in the various processes for producing sal ammoniac can be found in the scientific literature prior to the effective foundation of European industry. But it is difficult to prove how, if at all, the scientific knowledge was actually transmitted to the manufacturer who had to design large-scale, safe, and economical equipment, conceive of interdependent processes using the byproducts, and build the factories producing not just one but many marketable chemicals. As Multhauf states, "it seems very probable that the obscure men who were primarily responsible for the success of that industry were beneficiaries of the literature of popular science which flourished in the mid-18th century. But if the technology of sal ammoniac was ultimately dependent upon science, the scientists played a very minor role in the industrialization of sal ammoniac production, which was accomplished primarily by men whose principal qualifications seemed to have been ingenuity and a spirit of enterprise."[44]

The great technological feats of the mid-18th century—the hallmark inventions of the Industrial Revolution—came from men without formal training in science. The mechanicians who produced them, such as James Watt, were not unlettered men, and were not ignorant of the empirical science which they needed for their technical work, but this was not paced by new research at the scientific frontier.[45] James Watt did have contact with Dr. Joseph Black, the discoverer of latent and specific heat, but if Watt should share credit with anybody, it would be Matthew Boulton, the entrepreneur, rather than Joseph Black, the scientist.

This does not mean that there was no interplay between science and technology during this early period, nor that such contacts were not fruitful. Indeed, we have some very notable exceptions which prove the rule. For example, the need for bleaching and dyeing textiles and for porcelain to compete with the superb imports from the Far East stimulated basic investigations in high-temperature and analytical chemistry; a virtually direct line

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[44] Robert P.Multhauf, "Sal Ammoniac: A Case History of Industrialization," Technology and Culture, 6 (Fall 1965), 569–86.

[45] This view has been challenged by A.E.Musson and Eric Robinson, Science and Technology in the Industrial Revolution, University of Toronto Press, Toronto (1969).

can be traced from these technical needs to the discovery of oxygen and the definition of a chemical element which was to be the basis of the Chemical Revolution of the late 18th century. The classic examples for close relationship between science and technology in the 19th century were thermodynamics and electricity. In the former case, technology presented problems for science; in the latter, science presented potentialities for technology. But beyond these simple connections, what were the customary relationships between science and technology, the interactions as well as the reactions?

Men like Carnot and Edouard Seguin, who were responsible for primary theoretical advances in the field of thermodynamics, were engineers by profession. In his investigation of energy, James Prescott Joule always started with some specific technical problem, for example, the practical performance of an electrical motor with its production of work and heat. There is no doubt that the engine—the steam engine, and later the internal-combustion engine and the electric motor—presented problems which attracted the attention of scientists, and led to theoretical developments. But—and this is perhaps the crucial point—although technological advances spurred advances in theory, the theoretical knowledge obtained with such stimuli was very slow to feed back to technology.

Lynwood Bryant has shown, as a case in point, that the important steps in the development of the heat engine came from practical men not very close to theory, and the academicians, who understood the theory, did not invent the engine. Despite this, the change from the common-sense criteria of fuel economy to a new criterion of thermal efficiency marked a step toward the domain of abstractions, of invisible things like heat and energy, and was a major development in bringing scientific technology into being.[46]

The discovery of voltaic electricity as a result of the work by Galvani and Volta in 1791 to 1800 initiated a totally new period in the relationship between science and technology. Discovered in the laboratory, electricity inspired a number of empirical experimenters and gadgeteers but it found no practical use for nearly forty years, when the electric telegraph and electroplating appeared almost simultaneously. These applications provided an opportunity for many people of different intellectual and practical approaches to acquire experience with the new force.[47] The beginning of the electrical power industry lies in the design of generators for the electroplater, and widespread knowledge of circuitry came from the electric telegraph. From our viewpoint, it should be noted that electrical science and industry both required the measurement of new properties of matter. Conductors and insulators were, of course, well known and classified. The relationship between thermal and electrical conductivity had been identified and some studies of the

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[46] Lynwood Bryant, "A Little Learning," Wissenschaft, Wirtschaft, and Technik, Karl-Heinz Manegold, ed., F.Bruckmann, Munich (1969); a revised version, "The Role of Thermodynamics in the Evolution of Heat Engines," appears in Technology and Culture 14 (April 1973) 153–165.

[47] Some discussion of the role of plating in the beginning of the electric power industry will be found in C.S.Smith, "Reflections in Technology and the Decorative Arts in the Nineteenth Century," Technological Innovation and the Decorative Arts, I.M.G.Quimby and P.A.Earl, eds., University of Virginia Press, Charlottesville, Va. (1974) 1–62.

magnetic properties of the simple materials had been carried out well before 1800, but the richness of the field appeared only when experiments done in connection with the first Atlantic cable showed the great differences in the conductivity of copper from different sources and eventually related conductivity to the nature of the alloy. With the transformer came studies of iron alloys in the search for lower hysteresis losses, and the science and practice never thereafter parted company.

Up to this point, virtually all interest in the properties of materials was related to their mechanical properties along with reasonable resistance to corrosion. Even in the electrical areas, however, improvements and applications continued to come from the technology more than the science. Edison, the greatest electrical inventor of the century, was not schooled in electrical science and sometimes did things opposed to electrical theory. In Kelvin, we see a man of the future, but even he did not let his theory restrain his empirical genius. Well into the 20th century, men in close practical contact with the properties of materials had a better intuitive grasp of the behavior of matter than did well-established scientists.

The mutually reinforcing attitudes of mind which eventually led men to associate in MSE at first led technologists and scientists to place emphasis on different facets of the same totality of knowledge and experience. Scientists, in the simplifications that are essential to them, must often leave out some aspect which the technologist cannot ignore, and they usually overemphasize those aspects of nature that are newly discovered. It is commonplace to ridicule outmoded theories after new viewpoints have shown their strength. Yet, it can be claimed that the relegation of phlogiston to the dustbin of history by the 18th century chemists was something of a loss, for the properties of metals are indeed due to a nearly intangible metallizing principle—the valence electron in the conduction band in today's quantum theory of the metallic state. Similarly, the success of Dalton's atomic theory drew attention away from compounds that did not have simple combining proportions, and it left the very exciting properties of non-stoichiometric compounds to be rediscovered in the middle of the 20th century. Lavoisier's enthusiasm for the newly-discovered oxygen not only led him to believe it to be the basis of all acids—hence its name—but also to claim that its presence was responsible for the properties of white cast iron. Both were errors which took some years to eradicate.

Chemistry at the end of the 18th century turned away completely from the old concern with qualities and adapted a purely compositional and analytical approach to materials. This was an approach with which something clearly worthwhile could be done, whereas properties (being structure-sensitive as we now know) could only be handled individually by purely ad-hoc suppositions regarding the parts or corpuscles, which the ill-fated Cartesian viewpoint had made briefly popular. From analytical chemistry came a major triumph; new quantitative concepts of elements and atoms and molecules. These remain an essential basis of MSE although the control of composition is now seen less as an end in itself as an easy or cheap way of obtaining a desired structure.

The discovery of the presence of carbon and its chemical role in steel was a great achievement of 18th-century analytical chemistry. Indeed, until that time ignorance regarding chemical composition meant that there could be little basic conception of the nature of steel, and hence there was much confusion regarding both its definition and its production. A full understanding of the changes in the properties of steel on hardening could not be reached until it was learned in 1774–1781 that the carbon which helped produce the fire also entered into the makeup of the steel itself.[48]

The obvious value of this and related chemical knowledge eventually brought chemists as analysts into every large industrial establishment, but it also led to a temporary disregard of some promising earlier work on structure, which had begun by observations on the fracture appearance of bellmetal, steel, and other materials. The fracture test is extremely old and artisans to this day often judge the quality of their materials from the characteristic texture and color of broken surfaces. Early in the 18th century, the versatile scientist de Réaumur applied quite sound structural concepts to the making and hardening of steel and malleable cast iron, as well as to porcelain. He had interests ranging all the way from advanced science to traditional practice, and he carried out much of his work specifically for the purpose of reducing the cost of materials so that the common man could enjoy beautiful objects. Réaumur was the very model of a modern material scientist and engineer.[49] He had virtually no followers, for the leading physicists became increasingly absorbed by mathematical science under the influence of Newton and they joined the chemists who were proud of having thrown over the ancient intangible "qualities" for the new analytical approach.

The only scientific interest in the structure of matter at the end of the 18th century existed in the field of crystallography applied to the identification and classification of minerals. Some superb mathematics was developed around the concept of stacking among perfect crystalline polyhedra, but it failed to connect in any effective way with atomic theory, and few people even suspected that most real materials were composed of hosts of tiny imperfect crystals.

As a result, Réaumur's approach, which would have been fertile in the thought and practice of metallurgy had it been followed up, lay fallow for over a century—until Henry Clifton Sorby applied the microscope to steel (1863) and discovered that the grains which could be seen on a fractured surface were actually crystalline in nature and changed in response to composition and heat treatment. But even then, it was to take another two decades before the full significance of Sorby's discovery was recognized, when other metallurgists and engineers began to focus their attention on structure as well as composition.[50]

Yet these great strides in the fundamental understanding of the nature of metals and alloys occurred independently of—and indeed almost oblivious to—contemporaneous advances in practical metallurgy. While the chemistry of steel was being developed in Sweden and France, practical innovations in furnace design and operation and new methods of refining, consolidating, and

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[48] C.S.Smith, "The Discovery of Carbon in Steel," Technology and Culture, 5 (1964) 149–75.

[49] See Sisco, Réaumur's Memoirs on Steel and Iron. (Ref. 38, page 1–24)

[50] Cyril Stanley Smith, ed., The Sorby Centennial Symposium on the History of Metallurgy, Gordon and Breach, New York (1965).

and shaping wrought iron appeared in England. All this came about entirely without benefit of science, and yet it was a major factor in the social and economic changes referred to as the Industrial Revolution.

A major step in increasing the production of iron and decreasing its cost was Abraham Darby's solution, in 1709, of the problem that had been worked on for centuries, that of using abundant coal instead of charcoal for smelting purposes. This he did by coking the coal, removing volatile hydrocarbons and sulphur. Charcoal was in short supply and expensive, because of previous deforestation caused both by the needs of smelting itself and to provide land for agriculture. Darby's discovery was based more on a happy accident of nature than any scientific formulations, for both the ore and the coal available in Coalbrookdale, where Darby's iron works existed, were unusually low in the harmful impurities, sulphur and phosphorus.

Equally important was Henry Cort's improvement of the production of wrought iron. He developed the puddling process in which coke-smelted pig iron was oxidized on a large scale in reverberatory furnaces instead of in small batches in the earlier firing hearths, and he combined this with the rolling mill to give an integrated plant for the large-scale, low-cost production of bar iron in a diversity of shapes and sizes. This was in 1784 and it is rightly regarded as one of the chief contributors to the rapid development of industry and changing attitudes in the Industrial Revolution.[51] At about the same time, the English pottery industry was changing its scale and nature, partly because of new compositions and partly by more consciously applying new chemical knowledge and management techniques. In this, Josiah Wedgwood was an outstanding leader, though he undoubtedly got some inspiration from the scientific work on the continent and reports of the mass production techniques in the great Chinese factories. But, of course, the iron and pottery industries were only one part of a much broader organic change involving marketing techniques (in which Wedgwood himself was a pioneer), transportation with the expanding canal system, power becoming geographically unrestricted through the advent of the steam engine, a new sense of urbanization, and a growing middle class.

The next radical change in the iron industry was the making of low-carbon steels in the molten state. Before the 1860's, malleable iron had perforce always been consolidated at temperatures below its melting point, with inevitable heterogeneity in carbon content and entrapment of slag and other inclusions. Tool steel containing about 1 percent carbon had been made by melting "blister steel" in a crucible and casting into ingots from about 1740, but temperatures high enough to melt the low-carbon materials had to await, first, the discovery by Henry Bessemer in England (or William Kelly in America) that the oxidation of the impurities in the pig iron would themselves provide enough heat to melt pure iron and, second, (perhaps more important for a century, though much less in the public eye) the development of the efficient open hearth furnace by the Siemens brothers and its adaptation to steelmaking

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[51] H.R.Schubert, History of the British Iron and Steel Industry…to AD1775, Routledge and Kegal Paul, London (1957); Theodore A.Wertime, The Coming of the Age of Steel, University of Chicago Press, Chicago (1962).

by melting pig iron and ore together, or pig iron and scrap—the latter by the Martins in France.[52]

Though he implies otherwise in his autobiography[53], Bessemer did not come to his process through a study of new chemical and physical discoveries. He happened to see the unmelted shell of a pig of cast iron that had been exposed to air while being melted in a reverbatory furnace, and this started him thinking about oxidation. The thermal aspect of his process was also not anticipated, and his first experiments on blowing air through molten cast iron were done in crucibles set into furnaces to provide enough external heat. But, of course, he knew enough schoolboy chemistry and physics to realize the significance of what he observed, and had the energy needed to develop the process from an observation to a commercial success. His converter became almost a symbol of an age.

Like Darby, however, Bessemer was also the beneficiary of a happy environmental accident. He had ordered some pig iron from a local merchant without any specification, and it just happened to be unusually low in sulphur and phosphorus. His first licensees, using a poorer quality of iron, could not produce good steel; he bought back the contracts and employed some first-rate analytical chemists who found out what the trouble was. Moreover, even the best available iron had some residual sulphur which made the metal “hot-short,” i.e., fragile when hot. This, in turn, was corrected by the addition of manganese which had previously been used in crucible-melted steels but (as Robert Mushet who patented it recognized) it was particularly useful in “pneumatic steel” for correcting the effect of oxygen as well as sulphur. When added as high-carbon spiegeleisen, the ferroalloy simultaneously restored the burnt-out carbon to the level desired in the finished steel. None of these represented advanced scientific concepts at the time, yet all would have evolved far more slowly without the foundation of chemical understanding that came out of the 18th century.

The open hearth furnace was a direct result of new thermodynamic thinking, as was the related Cowper stove for efficiently heating the air for the blast furnace, although the invention of the hot blast itself had occurred in 1828 on the basis of a practical hunch. The Martin process was first simply used for melting and was advantageous in that it employed scrap, but combined with Siemens original plan to melt pig iron and ore in refining, it achieved great flexibility. Neither the converter nor the open hearth process could remove phosphorus; although an oxidizing slag in the presence of the lime can remove phosphorus, its use was impractical until a refractory for lining the furnace could be found that would withstand the corrosive effect of such a slag at the high temperatures involved. The Thomas invention of the basic process using magnesite or dolomite solved this—and changed the industrial map of Europe. This illustrates the intimate relationship between metallurgy and ceramics; all metallurgical processes are dependent upon the availability of materials to contain them.

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[52] Elting E.Morison, Men, Machines and Modern Times, MIT Press, Cambridge, Mass, (1966).

[53] Henry Bessemer, An Autobiography, Offices of Engineering, London (1905).

The 19th-century developments in metallurgy almost all aimed at the more efficient production of materials known for centuries. Chemical theory was helpful to guide improvements, and chemical analysis became essential in the control of both raw materials and processes. By the end of the 19th century, most major metallurgical works had their chemical laboratories, and it was through the analytical chemist that a scientific viewpoint found its way into the industry. Moreover, a new outlook on the part of the metallurgist was beginning to take form, by the comination of the engineer's concern with properties, the microscopist's new knowledge of structure, and a flurry of new empirical alloy compositions inspired by the increasing demands of the mechanical engineer.

The accidental discovery of age hardening in aluminum alloys in 1906 led to the zeppelin (with great psychological if not military effect in World War I) and turned metallurgical thought to a new field, dispersion hardening, of great practical importance and even greater theoretical significance.[54] More than anything else, this event revealed the richness of structure on a scale between the atom and the crystal and stimulated studies of composite materials of all kinds. Previously, the main metallurgical advances lay in the development of alloy steels. This had become a purposeful objective at the end of the 19th century, for most earlier attempts to improve steel had involved relatively small pieces of metal for cutting tools in which only hardness and wear resistance were needed. Today's alloy steels, of course, are those in which high strength and reasonable ductility are required throughout the entire section of relatively large machine components or structures, and the role of the alloy is more to control the depth to which quench-hardening is effective than it is to obtain higher hardness. The industrial use of modern alloy steels starts with Hadfield's high-manganese steel of 1882, soon followed by nickel steels in 1889 (at first for armament) and vanadium steels in 1904. The last were invented in France, improved in England, but most widely used in the United States—by Henry Ford. The requirements of the automobile were the principal incentive for the large-scale development of alloy steels, but the studies of them, at first largely empirical, profoundly influenced the growing science of metals by forcing attention to the complicated structural changes that occur during heat treatment.

Changes of materials can interact with society in ever-widening and often invisible ways. The entree of alloy steels that underlay the automobile and the change in suburban life that came with it is simply one example of the process. A century earlier the whole rhythm of life had been profoundly affected by improved methods of lighting; later came the refractory thoria mantle for the incandescent gas light, which was in turn largely replaced by the incandescent electric lamp; the latter became possible after a search for filament material had yielded first carbon, then tantalum, and finally, drawn tungsten wire of controlled grain size and shape. The incandescent lamp itself has been partly supplanted by fluorescent lamps depending on materials of quite different physics; still more recently lamps using high-pressure sodium vapor in alumina envelopes, resulting from the most advanced ceramic technology, altered the patterns of crime on city streets.

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[54] H.Y.Hunsicker and H.C.Stumpf, "History of Precipitation Hardening," in Sorby Centennial Symposium on the History of Metallurgy, Gordon and Breach Science Publishers, New York (1965) 271–311.

The development of cutting tools as part of the background of steel technology was mentioned previously. Tools, however, react significantly on all methods of production and even on the selection and design of whatever is being produced. For cutting operations performed by hand the traditional carbon steel, hardened by quenching and tempering, was adequate. In the middle of the 18th century, the uniformity of carbon steel (though not its quality) was considerably improved by the introduction of Huntsman's method of melting and casting it. His "crucible" steel was originally intended as a better material for watch springs, but once the smiths and toolmakers learned to work with it, it slowly displaced the unmelted steels for most exacting cutting applications. However, such tool steel softens at about 250° C and this temperature was easily reached at the tips of tools in power-driven lathes. Experiments to improve steel by alloying (including some notable experiments by the eminent Faraday in 1819) showed little advantage and did not disclose the greater depth of hardening in alloy steels which today is the major reason for using them. However, this line, beginning with naval armor plate in the 1880's, became industrially important to automobile manufacture around 1900.

Tungsten had been introduced into tool steels by Robert Mushet in 1868. His tool steel contained 9% tungsten and, when given a normal heat treatment, was found to wear much better than ordinary steel. Its use was economical because it needed less frequent grinding, but it did not produce any drastic change in the machine-tool industry. Then, in 1898, Taylor and White who were systematically studying the factors that affected machine-shop productivity, discovered that an enormous improvement could be derived from quenching a high tungsten steel from a very high temperature. Such steels were able to cut at much higher temperatures than ever before and the lathe was completely redesigned to stand the higher stresses resulting from the removal of metal at a faster rate. An even more spectacular change arose from the introduction of the sintered tungsten carbide tools in the early 1920's. In turn, this intensified scientific interest in sintering mechanisms, and an important new industry came into being—that of powder-metal fabrication (previously only used for tungsten lamp filaments). Yet, the consuming public sees such major advances only in the lower cost or higher precision of the final product.

The age-old abrasive shaping process was revolutionized at about the same time as metal cutting. Synthetic abrasives began with silicon carbide as a product of the electric furnace in 1891, culminating in synthetic diamond (which became commercial in the 1960's) and most recently boron nitrides. Modern mass production of precision parts would have been quite impossible without silicon carbide and related materials for grinding wheels, and the new generation of machines that utilize them.

THE NEW SCIENCE OF MATERIALS BASED ON STRUCTURE

Modern MSE, however, involves much more than metals. Perhaps the most dramatic changes in this century have been in organic materials, and for this we must return to the 19th century and the development of organic chemistry, moving from the simple inorganic molecule of Dalton into molecules of far more complicated structure. Simple atomic properties beautifully explained the composition of homologous series of compounds such as the aliphatic hydrocarbons. Then the fact that organic substances of the same composition could have vastly different properties—isomerism—forced attention to a richer molecular structure, though similar phenomena had been known much earlier in connection with elemental sulphur and carbon. Wöhler's synthesis of urea from inorganic compounds in 1828 was the first visible step to the union of the organic and inorganic worlds in chemistry, but it took a century and a half more before they merged via structure into a common science of materials. The isomerism of tartrates and racemates was discovered by Berzelius in 1830, and Pasteur showed, in 1848, that when crystallized the latter gave two crystal forms that were mirror images of each other and opposite in optical activity.[55]

The structure of molecules took on added meaning when the German chemist Kelulé saw that chemical formulae could designate or even model specific arrangements of atoms in the make-up of the molecule, instead of simply listing the number of atoms of each element.[56] His structural formulae for designating the associations of individual atoms in organic compounds gave a precise representation of the molecule. His flash of insight in seeing the ring structure of the benzene-molecule as distinct from the linear-chain character of the aliphatic hydrocarbon molecules not only served to distinguish these two great classes of compounds, but it provided a basic concept for understanding the nature of polymers which are so important today. In retrospect, it is curious that the 19th-century chemists tended to resist the idea that their formulae represented the real structure of their molecules: this approach was regarded as little more than a notational device. Only toward the end of the century did levels of aggregation beyond that of the simplest molecule begin to be of concern to scientists, and not until those who were concerned with structure at any level were ready to join with others could modern MSE begin.

Kekulé's benzene ring diagram soon had application in industry. Just a few years earlier, in 1856, a young British chemist, W.H.Perkin, attempting to make quinine artificially in a laboratory, discovered a purple dye which he named "mauve." This was the first of the synthetic aniline dyes, and represented the beginning of the coal-tar chemical industry. The benzene ring diagram showed the structural nature of these organic molecules, and provided guidelines for the discovery and synthesis of new ones. Under the stimulus of Perkin's discovery and others, the natural dyes, such as indigo, were soon replaced by synthetic ones. In the synthetic dye industry, as elaborated in Germany during the last half of the 19th century, we can see a prototype of what was to become one of the basic elements in MSE, namely, the coupling together of theory and practice, basic research done with an end-use clearly in mind. Although the first aniline dye had been discovered in Britain, it was in Germany that research chemists worked in laboratories which were attached to—indeed, were an integral part of—industrial chemical works.[57]

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[55] J.D.Bernal, Science and Industry in the Nineteenth Century, Routledge and Kegan Paul, London (1953) 181–219.

[56] Maurice P.Crosland, Historical Studies in the Language of Chemistry, Harvard University Press, Cambridge, Mass. (1962).

[57] John J.Beer, The Emergence of the German Dye Industry, University of Illinois Press, Urbana, Illinois (1959).

The primacy of the German chemical industry from the last quarter of the 19th century through World War II was undoubtedly a direct result of this fruitful coupling of research with production, and the converse effect of industrial activity on the liveliness of the academic laboratories can also be seen. The German dye industry is an early example of the fruitful interaction between laboratory and factory which was later to become one of the major prerequisites of MSE.

Eventually, from this approach, came whole new classes of synthetic organic materials: the plastics. Modern plastics date essentially from the development of Leo Baekland, in 1909, of phenol-formaldehyde compositions which can be molded into any shape and hardened through molecular cross-linking by heating under pressure. This precipitated an active period of scientific study of the synthesis and behavior of large molecules (both aiding and and being aided by biochemical studies of proteins) and gave rise to the industrial development of inexpensive easily fabricated materials for general use as well as many specially tailored materials in which desirable properties could be uniquely combined. There was, however, a prehistory of polymers in both the technology and science before Baekland’s great discovery.

Polymers based on natural products had been used for millennia in the form of lacquer. Many of these were combined with other substances to reinforce them or to change their properties as in today’s composite materials. Natural polymers such as ivory, tortoise shell, and bone had been artificially shaped under heat and pressure molding, and rubber had been used in fabrics of various kinds. None, however, was industrially important until the development of the vulcanization process in 1841. Vulcanized rubber and the heat-moldable natural resin from Malaysia called gutta-percha were extensively used as insulators in electrical apparatus. The first moldable totally-artificial plastic material was celluloid (nitrocellulose and camphor) first used for pretty trinkets but soon for shirt collars and eventually photographic films and numerous other objects such as batter cases. It was, however, dangerously inflammable. Synthetic fibers did not become commercial until the advent of cellulose acetate, “artificial silk,” in the 1920’s.[58]

The background of artificial organic materials in the form of fibers reaches back to suggestions of the great scientists Robert Hooke and R.A.F. de Réaumur in 1665 and 1710 respectively, but this did not bear fruit until the 1850’s when nitrocellulose was extruded into fine threads, already called “artificial silk.” Joseph Swan’s work on the development of carbon filaments for electric lamps led him to make fabrics from artificial fibers in the 1880’s, but commercial production stems from France. Other means of getting natural cellulose into fibrous form was via solution in alkaline copper solutions—a process in connection with which stretch spinning was first used, thereby permitting the formation of very fine fibers with oriented molecules—the cellulose acetate process; and the viscose process, in which cellulose was put into solution with alkali and carbon bisulfide. The last was for years the most popular, but in the late 1940’s cellulose-based processes were largely displaced by the introduction of synthetic polymer fibers. All these processes were used for other than textile purposes, notably the

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[58] M.Kaufman, The First Century of Plastics, The Plastics Institute, London (1963).

cellulose acetate airplane-wing "doping" and the base for photographic film. These developments gave the organic chemists and manufacturers experience with polymers, and the public acceptance of pleasant, low-cost garments made of "rayon" laid the ground for widespread acceptance of plastic products in general. Synthetic resins came into wide usage for reinforcing viscose fibers and improving the surface characteristics of fabrics.

The underlying chemistry and physics of polymers unfolded without much connection with the older inorganic material sciences. It seems certain, however, that in the future, the basic sciences of metals, ceramics, and organic materials will mutually enrich one another, no matter how diverse the manufacturing industries may remain. Emulating the earlier German chemical industry, scientists and engineers in the American plastics industry today work together in large research laboratories. Their contributions, which are an important part of the story of the evolving MSE, have led to many new materials—cellophane, nylon, dacron, teflon, synthetic rubber, foam rubber, etc.—which have entered our daily lives. This experience has also shown that new materials can be designed for specific applications almost as easily as machines can be designed on the basis of the principles of mechanics and mechanisms.

Crystallography had little relationship to practical materials until well into the present century. Its lively development from roots in the 17th century depended partly on its utility in the classification of minerals and partly on the attractive elegance of the mathematical formulation of the external shapes of crystals and later in the theory of crystal lattices and symmetry groups. Despite brilliant early insights, notably by Robert Hooke, into the relation between crystal form of chemical constitution, the concepts were not formalized until the very end of the 19th century. The application of even this knowledge to practical materials was delayed by the curiously-slow recognition that it is internal structure rather than external form that makes a crystal, and that virtually all solid inorganic matter is composed of irregular nonpolyhedral crystal grains packed together. A most important step was Sorby's establishment of methods for the microscopic study of rocks. Then, in 1863, he revealed the microcrystalline structure of iron and steel in which he identified seven constituents of different chemical and structural nature which were responsible for the well-known differences between various forms of ferrous materials.

Twenty-five years later, this began to interact with new chemical knowledge and especially with the growing body of chemical thermodynamics to permit observation and understanding of structural differences on a larger scale than that at which physicists and chemists had been working previously. Then, rather suddenly, the discovery of x-ray diffraction provided a tool for studying basic interatomic symmetries, and eventually all structural levels were conceptually connected. This discovery by von Laue and his associates in 1912 and particularly the prompt development of the use of x-rays in the study of the crystalline state by the Braggs in England completely altered the attitudes of pure scientists toward materials, and gave a framework within which all types of solids can be understood. It did to

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[59] John G.Burke, The Origins of the Science of Crystals, University of California Press, Berkeley (1966).

physics what the polymer molecule had done to chemistry.[60]

THE NEW SCIENCE OF MATERIALS AND ITS RELATION TO PHYSICS

The modern technologies of aerospace, nuclear engineering, semiconductors, and the like, coincided with the development of theoretical and experimental studies of materials which underlay the new and more sophisticated demand. As we have indicated, the new materials concepts had been developing throughout the 19th century and the first half of the 20th century. For example, the growing involvement of physicists in structure-sensitive properties synergized solid-state physics and metallurgy. As Cyril Smith has pointed out, “Theories of deformation, of the nature of inter-crystalline boundaries, of transformation mechanisms, and many other subjects popular today were advanced and discussed by metallurgists decades before physicists discovered that there was any interest in this scale of matter. But x-ray diffraction inevitably led the physicist into contact with a whole range of solids, and made imperfections unavoidably visible. By 1930 there had been postulated several different types of imperfection—and those resulting from gross polycrystalline heterogeneity and various types of mechanical and chemical imperfections within an ostensibly homogeneous single crystal. These models provided satisfactory explanations of many age-old phenomena. An extremely fertile period of interaction between metallurgists and physicists resulted, now, fortunately extending to those who work with ceramics and organic materials as well.” [61]

Perhaps the major conceptual change was the new way in which physicists began to look at matter. If they thought of the structure of matter at all, 19th-century physicists did so in terms of Daltonian atoms and molecules, finding therein the foundation of the superb kinetic theory of gases and all of the stereological variability they needed. The great physicist von Laue remarked that, in the 19th century, physics had no need of the space lattice. His own discovery of x-ray diffraction in 1912 changed all this. It provided an admirable experimental tool for studying atomic positions in crystals and it interacted fruitfully with the new quantum theory of solids. Only the opening up of a route to the even more exciting structure within the nucleus of the atom prevented this from becoming the main concern of physicists. As it happened, it was not until the late 1940’s that the new branch of physics, that of the solid state, began to take form and flourish. In the next decade, it came to be numerically the most important of the subdisciplines into which physics was dividing.

The development of many specialized branches of physics had resulted in some loss of the physicists universality that the proudly claimed early in this century. He cannot possibly be equally in touch with solid-state physics, biophysics, optics, nuclear physics, fluid dynamics, chemical physics, plasma physics, particle physics, high-polymer physics, and physics education, to

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[60] Paul P.Ewald, et al., Fifty Years of X-ray Diffraction. International Union of Crystallography, Utrecht (1962).
[61] C.S.Smith, Reference 24, page 1–17.

list simply the divisions of the American Physical Society and the associated societies within the American Institute of Physics, Yet, these specialized physicists all proudly claim their allegiance to physics, and their professional interests are coherently maintained. In the case of the field of MSE, there is even more diversity than in physics, and the sense of coherence is at present only rudimentary. Professional concern for all its branches is not instilled in university training, and it is not an essential consideration for maintaining status in the profession. Neither a metallurgist nor a polymer chemist nor a solid-state physicist working in the field of MSE tends to think of himself primarily as a materials scientist or engineer. Why is this? The intellectual, the technical, and the social needs all seem to favor the formation of a clearly-defined profession uniting the disciplines and providing an opportunity for a life’s work in the area made particularly rewarding by interactions with others in the whole field.

The difference between the two forms of association represented by physics and MSE appears to lie in history. The diversification of physics occurred by the gradual condensation of the subdisciplines, at first with no sharp boundary, within a pre-existing framework that encompassed them all. Conversely, all of the component parts of MSE, whether scientific, technological, or industrial had existed for centuries without much connection; the new unity has occurred by the joining of previously-defined entities rather than in the division of a larger entity into smaller parts. At the present stage of maturity, physics and MSE do not differ much in the structure and relationship of their parts, but the origin of the subdisciplinary divisions between the interfaces and the mechanism of their growth were vastly different. A highly specialized physicist classes himself with other physicists because at an earlier stage physics did include both fields embryonically. Solid-state physicists, polymer chemists, thermodynamicists, and designers or processers of materials have not yet had sufficient time to develop emotional attachment to the new realignment which is coming into being as a result of both social and intellectual factors. By its very nature, the formation of a new superstructure is harder to bring about than the progressive differentiation of a unified field into subunits because it entails greater changes of the units The present report, by illustrating both the difficulties and the potentialities of the new grouping will, it is hoped, encourage the formation of trial institutions from which might come the pattern of the future.

The properties of the materials that we fabricate and use derive only indirectly from the properties of the simpler systems that lend themselves to rigorous treatment by the physicist. The engineering properties mainly characterize large aggregates of atoms and stem from the behavior of electrons and protons within a framework of nuclei arranged in a complex hierarchy of many states of aggregation. By way of analogy, one cannot visualize the Parthenon simply by describing the characteristics of the individual blocks of pentellic marble that went into its construction, still less by analyzing the grain and crystal structure of the marble itself. The Parthenon would not exist without all these but it is more than an aggregate of crystals, more than a collection of marbles; it is a structural masterpiece reflecting even embodying, the spiritual, economic, and technological values of a great civilization. To understand a material it is necessary to know the numbers of different kinds of atoms involved, but it is the way these are put together which basically characterizes the material and accounts for the properties that an engineer uses. The main feature of the new approach to the science of materials is recognition of the importance of structural interrelationship, just as on an engineering level it is an awareness of the interrelationship between a given component or device and the larger system in which it is operating; correspondingly on the social level, each family's needs and deeds must fit in with others to make a world of nations.

The new approach to the science of materials is based on the recognition of the full complexity of structure and the fact that the properties depend on it. Once this principle was grasped, materials scientists and engineers could apply it to all kinds of materials and find the underlying unity behind the many classes of materials that had in previous times been studied, produced, and used in totally separate environments.

Materials science is limited, of course, by the laws of nature but there are enough laws and enough atoms of different kinds to produce an almost endless diversity for the materials engineer. There are many new complex structures to be discovered and exploited. Materials engineering is more analogous to the geographic discovery of new continents and cultures than it is to the discovery of the principles of gravitation, navigation, or meteorology. To be sure, materials engineers have to work within the laws of nature, but they are also at home in areas too complex for exact fundamental theory and have learned to combine basic science and empiricism.

Although this new approach to materials took form first in the field of metallurgy, the principles have meaning for all materials—ceramics, cement, semiconductors, and both biological and synthetic organic polymers. It is beginning to influence geology, as in the past geology has influenced it. Composite materials with structures combining two or more of the basic types of materials on a scale greater than the atomic have, perhaps, the greatest future of all. The dominance of crystalline materials is already being challenged.

MSE is as useful to those concerned with production as it is to those who wish simply to understand. On one hand, studies of solidification, deformation, and phase changes apply to the processing of all kinds of material, and on the other, methods of fabrication that have been successfully developed for one material can solve production problems for another. The influence of ceramics on powder metallurgy is a classic example, but note the transfer of metal-shaping and joining techniques to the new polymers and the application of metallurgical thermodynamics, primarily stimulated by the requirements of the steel industry, to the production of other metals.

When science began to be applied to materials technology, it was done so first at the production end, for only here was it economically feasible. The complexity of structure-sensitive properties which were of concern to the user prevented the application of helpful science until quite late. The early materials were general purpose ones and the consumer, whether an artist or an engineer, selected what he wanted from a small catalogue. Science at first controlled the chemistry of production, the efficiency and reliability of smelting. Not until well into the 20th century did the structure-property concept take hold, but when it did a common basis was provided not only for iron and nonferrous metals, but also for ceramics and, more recently, organic materials within the same body of knowledge. Science not only offered an explanation for the many aspects of properties that had been discovered empirically, but it pointed the route to improvement and even totally new materials designed with specific properties in mind.

The end-use and the preparation of materials have now been joined in MSE. No longer is the primary producer's profit dominant, but profit comes from the best analysis of needs and possibilities. The 19th-century engineer selected the best material that was available and improved it marginally. The 20th-century engineer can state what he wants and has far more options. Although in both cases economics dictate, it is now at least as much end-use economics as production economics.

Another relevant factor is the closer junction between science and engineering at all levels. Specialization is needed now more than ever before, but it must be in resonant communication. A new level of organization seems to be emerging, with specializations deepening, but with enhanced communication between them. Diversity is an essential characteristic of MSE, but there now exists a means of communication. The science of materials, their engineering design, and production engineering at both the chemical and mechanical stages are all interrelated; none is in isolation for each affects the other. A new kind of man is necessary to encourage the liaison, a kind of intellectual manager who, knowing something of many fields, makes his contribution by promoting balance among the disciplines and foreseeing areas likely to become limiting. As it happens, each material has its own complex of requirements, for even when using the same basic shaping techniques, the temperature and forces involved and the sensitivity to atmospheric and other contamination are different. Moreover, the availability of special properties means special uses, and the more specialized the material the more the materials engineer must know the effect of all production variables on successful application. One man cannot possibly encompass all aspects with equal detail, but the validity of MSE lies in the recognition that a certain commonality of problems exists.

The new structure-property viewpoint has served to bind together and to enrich the many strands of pure science which interact in the field of MSE. Without this contact, the crystallographer would focus mainly on ideal crystals; with it, he has been made aware of not only the difference between monocrystalline and polycrystalline matter, but also with the whole range of crystalline imperfections. For the first time in history scientists have been able to contribute to the understanding of structure-sensitive phenomena. Even in 1920, for example, textbooks on the properties of matter completely ignored most useful properties of interest to the metallurgist, and the strength of materials, as taught to the practical engineer, was essentially a simplified form of elasticity theory, once an important part of mathematical physics.

ENGINEERING ATTITUDES TOWARD MATERIALS IN THE 19TH CENTURY

It should be noted that studies of the strength of materials during the early part of the 19th century were centered in France, where the Ecole Polytechnique, the famous French engineering school, had been founded in the last decade of the 18th century and where theoretical investigations of both technical and scientific phenomenon reached a high mark. Governmental policy fostered not only the foundation of this school by also encouraged its graduates to use a scientific approach to practical problems. In the Department des Ponts et Chaussees and related enterprises, the best theory and the best empirical tests were merged, and contact with practical problems inspired some advanced pure mathematics at the hands of Navier, Poncelet, and others.[62]

For most of the 19th century, England's contribution to the study of the strength of materials consisted mainly of empirical investigations of the strength of various building materials. William Fairbairn (1789–1874) and Eaton Hodgkinson (1789–1861) carried out tests on beams and other shapes of wrought iron and cast iron, and iron-framed buildings became common. In Germany, engineering schools based upon the French model were founded, but a more practical bent was given to the education and their students mainly took positions in private industry.

The growth of the railroads led to many, primarily empirical studies of the strength of materials. Fatigue in metals was first studied in connection with railroad and bridge components. An example of the empirical approach employed by British engineers is the fatigue-testing machine (consisting of a rotating eccentric which deflected a bar and then released it suddently), Captain Henry James and Captain Galton concluded that iron bars will break under repeated loads only one-third of which was needed to break them on a single application.

Several advanced industrial nations had set up material-testing programs or laboratories, and an International Congress for Testing Materials was established. In the United States such official testing had begun with the examination of iron for boilers in 1830[63] and was extended in the 1850's with emphasis on materials for cannon. A Board for Testing Iron, Steel and Other Metals was appointed by the President in 1878. Its report issued ten years later includes innumerable original tests and a comprehensive study of the state of knowledge on materials, mostly metallic.[64] The aim was limited to the determination of the pertinent properties of materials that were available, carefully characterized by chemical analysis and by a description of the method of manufacture. Nevertheless, these programs and the carefully-

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[62] Stephen P.Timoshenko, History of Strength of Materials with a Brief Account of the History of Theory of Elasticity and Theory of Structures, McGraw-Hill, New York (1953).

[63] John G.Burke, "Bursting Boilers and the Federal Power," Technology and Culture, 7 (1966) 1–23.

[64] Report of the United States Board Appointed to Test Iron, Steel, and Other Metals, 2 volumes, Government Printing Office, Washington, D.C. (1881).

written specifications under which materials were to be purchased forced an intimate contact between government, manufacturer, engineer, and scientist of a type foreshadowing MSE. The properties measured were initially almost entirely the mechanical properties of concern to the engineer and the materials producer, simply aimed to balance these against the requirements of fabrication. In the 1890's, metallurgists were beginning to study microstructure in relation to mechanical properties, and other properties were becoming important, especially in connection with the electrical engineering industry. Another kind of man investigated electrical and magnetic properties of materials for their scientific interest.

In the first two decades of the 20th century, theoretical physicists began to understand the interior of the atom, and developed quantum mechanics which gave a marvelous key to the differences between classes of solids. This interacted nicely with the findings of the new x-ray diffraction techniques, and real materials became a concern of the physicist for the first time. Not, however, until after World War II did solid-state physics become a well-recognized part of either physics or materials science. Then, in addition to ideas and sophisticated instrumentation for structural studies, physicists contributed techniques for measuring properties of materials—magnetic, electrical, thermal, and optical properties—whose studies had been previously largely a matter of guesswork.

In the 1920's, metallurgy was already beginning to move from its age-old chemical orientation to consider the properties of materials in terms of both composition and microstructure. Increasingly, the metallurgist found stimulation by working on topics that impinged on physics, to the advantage of both fields.

This changing emphasis did not mean that metallurgy became absorbed into physics any more than it had been absorbed into chemistry at an earlier date; instead, the metallurgist had uncovered phenomena which, in a sense, defined problems for both the chemist and the physicist. Nor did the newly-forged links with physicists require the metallurgist to lose contact with chemists; rather, the chemical component of MSE will be enriched in the future by the links with the organic traditions of the polymer chemist and the biochemist. By the end of the 1950's, materials science had been transformed into an multidisciplinary activity, utilizing tools, concepts, and theories from many different branches of science.

The growth of the scientific technology in the study of materials during the 19th century parallels a similar development in other fields of engineering.

The classic examples usually cited in studies of science-technology relationships in the 19th century are thermodynamics and electricity. In the former case, technology presented problems for science; in the latter, science presented potentialities for technology. The materials field incorporated both. Technology was also drawing closer to science in another way: one of the most important was the notion of the development of engineering "laws" based on precision, quantification, and mathematization in the form of semi-empirical equations. "Engineering science," differing from "pure science" in its motivation was carried out by men who occupied positons intermediate between the pure scientist and the practical engineer.[65] In both instances, objectives were limited to permit the formulation of mathematical relationships, but those of science were self-chosen to be soluble while those of engineering were set by the importance of the need. The engineer could not be satisfied just with understanding something in principle; it had to work, but he could use in his equations many empirically-measured coefficients, even of obscure origin. Furthermore, there were many natural phenomena not investigated by scientists but still meaningful to technologists, and so it was necessary for the technologists to conduct their own scientific investigations in some areas in more detail and on more materials than might be needed for the validation of scientific principles.

As technology has become more scientific and mathematical, and as scientists and engineers tend to work together on many problems, the old distinctions between them are disappearing because each absorbs part of the other’s viewpoint. In many cases, we must look into the context in which the work is done in order to decide whether it is scientific or technological. For example, the engineer often discovers gaps in basic scientific knowledge which must be filled before his technological task can be completed. The engineer fills the gap by doing what in another context would be called fundamental research, but because he needs it, it is called applied research.[66]

On the other hand, scientists often do engineering in the development of their instruments—as in the building of telescopes, in the improvement of high vacuum techniques, and the production of high voltages in particle accelerators—and pure science is often conducted by those with practical aims, for example, the basic studies of recrystallization which came out of work on tungsten lamp filaments and the semiconductor research inspired by wartime radar needs. Early in the 19th century, Faraday’s work on optical glass was classic (though not industrially fruitful), and E.Schott’s research on new glass compositions in the late 1800’s was a model MSE of scientific and industrial coupling which gave Japan a virtual monopoly on optical glass until World War I forced other countries to copy the pattern.[67]

The purposes, the methods, and the goals of scientists and technologists remain different, but the two kinds of practitioners have become more understanding of each other’s roles and capabilities. Nowhere is this more true than in the field of MSE.

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[65] Layton, “Mirror-Image Twins.” See Reference 43, page 1–26.

[66] For a review of the relations between science and technology, see the series of articles by Melvin Kranzberg: “The Unity of Science-Technology,” American Scientist, 55 (March 1967), pp. 48–66; “The Disunity of Science-Technology,” American Scientist, 56 (Spring 1968), pp. 21–34; “The Spectrum of Science-Technology,” Journal of Scientific Laboratories 48 (Dec. 1967), 47–58.

[67] R.W.Douglas and S.Frank, A History of Glassmaking, G.T.Foulis & Co., Henly-on-Thames (1972).

THE TECHNOLOGICAL REVOLUTION OF THE TWENTIETH CENTURY

Twentieth-century technology has been characterized by major changes in approach, method, and organization. The change in approach is manifested by the merging of science and technology, as indicated above. Change in method includes the introduction of purposeful and systematic attempts to innovate in order to meet specified needs and wants. The change in organization is reflected in the phrase “Research and Development” (R & D), which involves the employment of teams of people representing different disciplines—a phenomenon unique to recent times.[68]

These characteristics of the technological revolution of our times are to be found in different fields. For example, recent advances in agriculture at least match those in MSE, and are characterized by some of the same elements: the application of scientific study to the basic biology (plant genetics and the mechanism of growth), to the chemistry of insecticides and fertilizers, and to the technology of irrigation as well as the harvesting and preservation of agricultural products. Most important was the interaction of all these with each other—and with the economic and practical environment.[69]

This technological transformation in the 20th century seems to have been primarily dependent upon the organization of brainpower, that is, knowledge. There are many nations in the world today which remain underdeveloped despite their possessions of vast natural-materials resources, while some materials-poor nations are among the most prosperous. Partly, this is because the latter have undergone industrialization and hence have built-up industrial strength in the past, which continues its momentum; but largely it is because they possess know-how, the knowledge which enables them to organize their technology to overcome deficiencies in energy or materials. This state-of-mind is stimulated by productive partnerships between people of quite different motives, representing a great variety of disciplines, and associated with many different institutions. This is especially so in MSE.

The union of science and technology characteristic of American technical advance in so many fields has had some spectacular successes in MSE. Indeed, MSE was central to one of the greatest “breakthroughs” of the past quarter century, the development of semiconductors. Previous technology contributed little to this innovation; the first observations came from empirical studies by physicists of the electrical behavior of all available materials in the 19th century. The first commercial utilization of semiconductors (excluding carbon) was the Nernst lamp of 1901—then followed copper-oxide rectifiers, silicon-crystal radio receivers, and eventually radar, which was associated with some theoretical progress during World War II. The major advances in both theory and practice were made in 1947–49 in an industrial laboratory—the Bell Telephone Laboratory—where the transistor was developed by a combination of theoretical and experimental scientists and technologists, doing

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[68] W.David Lewis, “Industrial Research and Development,” Technology in Western Civilization, Melvin Kranzberg and Carroll W.Pursell, Jr., eds., Oxford University Press, New York (1967) Vol. II, chap. 40.

[69] Wayne D.Rasmussen, “Scientific Agriculture,” Ch. 22 in Vol. II, of Kranzberg and Pursell, Technology in Western Civilization.

everything from the development of special materials through device technology to the most fundamental physics of matter and circuitry.[70]

The recent growth of MSE can, in no small measure, be attributed to the increased recognition by industry of the value of physics: this new attitude toward materials has merged well with the qualitative structural approach that had ripened quite independently within the metallurgical profession. The interaction worked both ways: whereas it might be said that the physicists took the lead in semiconductor research, the quantum theory of alloys began as alloying rules developed somewhat empirically by an academic metallurgist, Hume-Rothery, before it became respectable physics.[71]

Similarly, chemical thermodynamics inspired extensive investigations of equilibrium diagrams based on thermal and microscopic analysis of alloys. Metallurgists soon found many metastable structures about which thermodynamics had said nothing, and, interacting with engineers, they used the microscope to study the effect of deformation on microstructure. Only much later did such phenomena become part of the purer science, or influence work on other materials such as polymers and ceramics.

One hears much these days about the trend toward increased specialization in all fields. This is certainly true of the component parts of MSE; and yet the field as a whole ha a characteristic which runs counter to this. For although there are many disciplines involved in MSE, it is in their multidisciplinary cohesion that the value lies. MSE by its very nature encourages communication among practitioners of different disciplines; it also encourages people to learn more about auxiliary disciplines; and, most importantly, it demands interaction among basic research, applications, and means of production. It is this systems approach which helps distinguish MSE from its individual predecessor disciplines. Although disciplines are still needed, there must be cross-fertilization among disciplines in MSE, and its practitioners must bear the whole in mind while peering more deeply into their separate parts. The common structural principles underlying the properties of various classes of materials make this possible—and, in fact, underlie the fruitful contributions which the different disciplines can make to the understanding and development of materials.

The new approach entails viewing a host of formerly unrelated activities and processes as parts of a larger, integrated whole. It permits today's scientists and technologists to speak of "materials" as well as of steel, glass, paper, or concrete. True, each of these has its own—and very old—technology. But the generic concept of materials represents different arrangements of the same fundamental building blocks of nature. The "materials revolution" allows us to decide first what end-use we want and then select or fashion the material to fulfill that need.[72]

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[70] Charles Weiner, "How the Transistor Emerged," IEEE Spectrum 10 (Jan. 1973); G.L.Pearson and W.H.Brattain, "History of Semiconductor Research," Proc. Inst. Radio Engineers 43 (1955) 1794–1806.

[71] W.Hume-Rothery, "The Development of the Theory of Alloys," Sorby Centennial Symposium on the History of Metallurgy, C.S.Smith, ed., Gordon and Breach, New York (1965) 331–46.

[72] Materials Science and Engineering in the United States, Rustum Roy, ed., Pennsylvania State University Press, University Park, Pa. (1970) 117.

An important aspect of 20th-century technology is a change in the organizational form in which innovation appears, and this is particularly the case in MSE. The old idea of separate or individual inventors working in isolated fashion on problems of their own selection has been largely replaced by R & D groups working toward a defined objective in an industrial research laboratory, a university laboratory, or a government laboratory, all of them bringing together specialists in different scientific and engineering specialties. This kind of application of science to technology was already visible in the 19th century in the optical-glass industry, in the German dye and pharmaceutical industry, in the development of the telegraph and cable, and in the embryonic electrical industry; but its systematic application on a large scale is a product of the 20th century.[73]

The American experience in industrial R & D shows the influence of the competitive forces characteristic of a capitalist economy. At the same time, this industrial utilization of science fostered a degree of cooperation, first between business units themselves and then among various types of business, governmental, and private organizations, that expanded and deepened over the course of time.

Included among the institutions carrying on R & D was the university laboratory; it became involved in a variety of external relationships through the consultative activities of its staff members, and later through governmental sponsorship of R & D. A substantial part of the latter support was through the medium of interdisciplinary laboratories (IDL's), which became an important vehicle for governmental sponsorship of materials research in the universities.

If, in this historic section, we have overemphasized metals, it is mainly because the history of metals has been more thoroughly explored than that of other materials. This, in turn, is partly a consequence of the fact that it was around metallurgy that the modern science of materials began to appear. There has been no history of building materials, for example, which attempts to explore both the science and the practice. Ceramic materials, with their spread from utilitarian objects to the greatest works of art, both inspired and benefited from science in the 17th and 18th centuries more than did metallurgy, but the many good histories of ceramics ignore science in favor of technology, and even the technology attracts only an infinitesimal fraction of the attention paid to ceramics as art forms. Writings on the history of organic polymers tend to be superficial, except for a few articles written with special emphasis on the work of one man or company. Moreover, there are few histories of the pure sciences themselves which give adequate attention to the continuous flow of practical problems that have come from men working with materials in novel situations. The level of complexity arising from materials interacting with everything that human beings have done and much of what they have thought for more than ten millennia precludes the presentation of a picture that is both accurate and simple, just as the complexity of materials themselves precludes description by a few simple equations.

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[73] Peter F.Drucker, "Technological Trends in the 20th Century," Technology in Western Civilization, II, Kranzberg and Pursell, eds., ch. 2. (See ref. 68.)

RECOGNITION OF MATERIALS SCIENCE AND ENGINEERING AS A COHERENT FIELD

The aim and very purpose of all technology is to respond to human needs as defined in some way by society, though, of course, technology also interacts with society to stimulate new expectations and to offer new possibilities for development.

Throughout history, military requirements—either during times of war or in preparation for war—have helped focus and intensify the pressures for materials development. It was quite obvious in World War II that: (a) modern industrialized warfare with its insatiable demand for some materials created critical shortages, and hence stimulated research for substitute materials and improved processing techniques, and (b) sophisticated weaponry required materials with specialized characteristics which an older and more conventional technology could not provide.

In the U.S., particularly critical were those materials that had to be imported; rubber, mica, quartz, and many of the alloying elements for steels. Research on substitutes—particularly synthetic rubber and the National Emergency steels—provided a dramatic example of the utility of the new science. Furthermore, the acceleration of innovations in jet aircraft, rockets, and nuclear energy brought to the fore critical limitations regarding the performance of materials at high temperatures. And the needs of communications, radar, and the proximity fuse made everyone aware of semiconductors and precipitated intense activity in the immediate post-war period. The critical needs for materials during World War II thus forced engineers to recognize the importance and broad potentialities of substitutes and caused a heightened sensitivity to the possibilities of developing entirely new materials of radically different properties. At the same time—and perhaps more importantly—the War inspired close cooperation between pure scientists and engineers of many different disciplines, suggesting patterns of effective interdisciplinary research that persisted into peacetime. Only about one out of ten companies using metals in a 1940 survey had a materials department; over half had such departments by the 1960’s.[74]

Within a few years after World War II, when the U.S. had entered into the Korean War, a national committee—the Paley Commission—was appointed to study the adequacy of materials supply. At that time, the question seemed to center on shortages of already-existing materials rather than the development of new ones. Such shortages were real. As the 1950’s began, the U.S. was simultaneously involved in the Korean War, was assisting in the restoration of Europe’s industry through the Marshall Plan, was aiding underdeveloped countries, and was still meeting the huge pent-up consumer demand following World War II, often with capital plant which had outlived its usefulness and needed to be replaced. Moreover, the concept of national preparedness during the Cold War made it seem essential to stockpile strategic materials and to build up sufficient industrial capacity for future emergencies.

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[74] Henry R.Clauser, “Materials Effectiveness, Materials Engineering, and National Materials Policy,” in Problems and Issues of a National Materials Policy. Committee Print, Committee on Public Works, U.S. Senate, 91st Congress, 2nd session (Washington, 1970) p. 178. This document, consisting of papers presented at the Engineering Foundation Research Conference on National Materials Policy (July 1970) contains a number of papers which have been helpful in preparing this section of the report.

The strategic requirements as America entered the Cold War era caused the Department of Defense to sponsor many investigations into materials with potential for high-temperature service, especially the entire family of refractory metals, but including many nonmetallic and composite materials. The problems were scientific as well as technological; at high temperatures, problems of oxidation, diffusion, phase change, and loss of strength often became paramount. Brittle fracture, stress-corrosion cracking, and other means of disastrous failure also attracted theoretical studies. From investigations of clad and composite materials came a new appreciation of heterogeneity on the scale that had been largely ignored since the days when the duplex steel of Damascus inspired so much research in Europe.

The advent of Sputnik posed still new challenges for the growing field of MSE. There was sudden need for the development of new materials possessing esoteric qualities for special applications in space. Furthermore, the usual engineering parameters of economy were of secondary consequence, provided the rigid performance requirements of the outer-space environment could be met. The space program also meant that governmental support for advanced new materials came from a civilian agency, NASA, in addition to AEC and the Department of Defense.

Other sophisticated materials requirements also made themselves felt. The decision to build a supersonic transport gave added urgency to titanium technology, a field that had been heavily supported by the Department of Defense since the late 1950’s. Although public opposition has relegated the development of an American supersonic transport to near-limbo, titanium remains a strong, corrosion-resistant, high-temperature structural material for other uses; much of what has been learned about the basic characteristics of this metal, its alloys and treatment, including rolling, forging, machining, and joining, will remain permanently valuable. Likewise, the requirements for turbine blades to withstand operating temperatures several hundred degrees higher than those in existing aircraft engines also prompted much materials research, and stretched the very limits of knowledge.

Similarly, as the forefront of nuclear-energy application moved from weapon to power, the material limitations broadened. In addition to the need for conventional materials of usual stability, reactors demanded dramatically unusual combinations of properties. Not only were high- or low-neutron absorption at various energies required (a nuclear property completely beyond the concern of the earlier materials professional), but the materials had also to resist radiation damage and corrosive environments under hostile conditions. Especially challenging has been the swelling of nuclear-fuel elements and graphite during reactor operation. As long as only thermal (low-energy) neutrons were involved, it could be largely controlled by the use of ceramic (uranium oxide) fuel and by dispersion of the uranium in a ductile matrix, but the new generation of breeder reactors using fast neutrons has raised the problem all over again in far more acute form. Fortunately, radiation damage itself is a useful tool in the fundamental studies of materials, and the problem has caught the interest of many fundamental scientists to the benefit of knowledge, development, and practice.

In brief, new military demands, the requirements of space, and new demands from fields in nuclear energy, missiles, rockets, communications, and the like entailed new challenges to many fields of science and technology, and often, indeed, they were factors that paced progress. Materials were central to all.

The most advanced technological achievements today require in their materials the presence of some property to an extreme degree, combined with reasonable stability and formability. This is very opposite of the age-old materials which typically had to serve for many purposes interchangeably.

Since the late 1960's a profound change in societal attitude has forced a new concern upon the technologist and the industrial establishment built upon his work. Through most of history, almost anything that the technologist could do was of some value to the society for, even if unbalanced, it helped to feed and house people, improve their health, and facilitate their communication with each other. Today, however, the increased density both of technologies and population makes obvious the necessity for some control within the broader framework of overall societally-oriented incentive. This puts new demands on all engineers. No longer can a smelter pour SO2 freely into the atmosphere. Modern plastics, effective detergents, and new ways of packaging products are all fine achievements from the immediate consumer's viewpoint, but they raise many societal problems when the entire material cycle is taken into account. Of course, the engineer has always been accustomed to working toward the balancing of conflicting factors, but in this case, neither he nor anyone else anticipated the broader problems until they had reached considerable magnitude.

The problems that now face the materials engineer are technically soluble if properly tackled. Fuel and raw materials can be produced without destruction of the environment, and processes can be developed for the efficient collection and distribution of waste materials of all kinds. The recycling of scrap has been an important part of the metals industry from the beginning, and in developing countries is almost complete even today. The emphasis on the direct cost of primary production needs to be supplemented by a broader view. It is a question of seeing the problem as a whole, of designing a system that includes the economics of disposal or recycling as well as the efficient production of a serviceable part.

GOVERNMENT SUPPORT OF MATERIALS RESEARCH

The new approach to the understanding of the behavior of materials and application of this new understanding to the processing and use of both old and new materials had already begun in the research laboratories of many science-based industries before the federal government became involved in providing massive financial encouragement for the new field of MSE. At least one university—the University of Chicago—used private funds to establish a full-fledged interdisciplinary materials research institute long before government-financed interdisciplinary laboratories became popular. It would be a mistake, therefore, to believe that MSE was created by administrative fiat and by federal funding, as is sometimes believed by those who see only the tip of the iceberg. In fact, the concept and applications of MSE had already made vital contributions to the nation's economy and defense even before many scientists and engineers had come to recognize their affinity with others involved in the same or similar fields.

The role of federal government was to accelerate and stimulate these developments;[75] In brief, to "institutionalize" the materials field, to accelerate the formation of this new field of study and practice—thus identifying a new "multidiscipline." It did this, perhaps unconsciously, by supporting intensive research of a scientific and technological nature on some specific materials (for example, titanium), by sponsoring economic studies of the nation's material needs, by supporting university research laboratories dealing with both specific and general materials problems, and finally by establishing interdisciplinary laboratories for materials research at several universities. The greatest result of the latter laboratories has been the training of scientists and engineers in an environment which, by intent, fostered an awareness of the many-sided nature of the field.

It should be pointed out that the philosophical principles and political practices underlying federal support of MSE are not unique to that field, although the instrumentalities employed by the government to develop MSE were unique. The governmental approach to MSE involved new means for making its support effective, and served as a useful model for advancing other scientific and technological fields to meet new and changing national goals.

We need not be detained here by the long history of federal support of scientific research and technical developments; that has existed ever since the foundation of our Republic.[76] The triumphs of science and technology during World War II convinced the country's policy makers that not only the military power but also economic power and social growth were dependent upon the nation's scientific and technolgoical capabilities. Two decades later, it was recognized that the spiritual needs of the nation were also a function of its scientific and technological capabilities, and the direction of the vast enterprise became a matter of prime concern.

Politics, at first defined largely in military and aerospace terms, determined a rising level of national support for scientific and technical enterprises. It is not surprising that MSE participated in the general growth of the scientific-technological activity in this country. But there was more to it than that. Virtually all developments in the new areas of science and technology hinged to some degree on materials that were not in existence. The need for materials which would function in the frigid near-vacuum of space, as well as in the hot blasts of rocket engines, the requirement to miniaturize electronic equipment for control and communication, the need for materials stable under the heavy radiation and high temperatures of nuclear reactors, and many similar problems could not be solved with materials to be found "on the shelf" of existing suppliers.

The readiness of old industries to do new things, the appearance of many scientifically-oriented small industries, the growing awareness among scientists of the challenge lying at the peripheries of their professions, and the

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[75] We are indebted for much of the following material to an unpublished seminar paper by Joseph Leo, for the Case Western Reserve University Program in Science, Technology, and Public Policy; the paper (May 1971) was entitled "Government-Sponsored Research and the University Materials Community."

[76] A.Hunter Dupree, Science in the Federal Government, Harvard University Press, Cambridge, Mass. (1957).

increasing success of end-use-oriented development work, all interacted to suggest that a new field of materials science and engineering might be forming. Many university departments changed from “metallurgy” to “metallurgy and materials science” or “materials science and engineering,” thus indicating their changing objectives; there was an analogous shift from “mining” to “mining and metallurgy” and then to “metallurgy” in the 1920’s and 30’s. As in the latter sequence, these changes were accompanied by some inevitable loss, but the broader character of the new organizations will in time correct this. It remains to be seen whether the new MSE grouping is viable at universities. In order for this evolutionary interactive process to continue, there will have to be no slackening in the ongoing development of the specific sciences and areas of engineering knowledge that compose MSE.

In 1957, the distribution of funds for research in materials was divided about as follows: solid-state physics, 35%; metallurgy, 29%; and ceramics, 10%; with smaller amounts going to research in other related fields, such as physical chemistry, and, of course, more in the application of known materials for various military devices. Yet the decade from 1947 to 1957 was precisely the time when exciting developments in quantum theory of solids and dislocation theory, as well as electron microscopy and other research techniques, were bringing the metallurgist and physicist together for interdisciplinary studies of materials. It was also a time when interdisciplinary activity already flourishing in industrial research laboratories began to place demands upon the universities for the training of research scientists who could work in this newly-evolving environment. Concomitantly, mission-oriented governmental agencies, such as the Atomic Energy Commission and the Department of Defense, were becoming increasingly interested in new materials with exotic qualities for use in new energy sources, new weapons systems, and new propulsion schemes.

A number of studies indicated the need for the allocation of research funds along new directions. Several reports pointed toward the creation and development of an institutionalized form of support for materials science and engineering. The “Sproull Report” (named for Dr. Robert L.Sproull, a physics professor at Cornell, who was later to become head of the Advanced Research Projects Agency (ARPA) of the Department of Defense (DoD)) spoke of the need to support research in solid-state physics. Dr. C.F.Yost of the Air Force, at about the same time, proposed a center for research on the growth of crystals; and the Air Force, in an assessment conducted by a group at Woods Hole in 1957 also stressed the importance for greater research in materials. A Department of Defense/Materials Advisory Board study (nicknamed the “Dartmouth Report” because of the place where the conference was held) also advocated the allocation of more funds for materials research in 1957–58. The same recommendation was made in a report on “Perspectives in Materials Research” issued under the auspices of the Office of Naval Research and the National Academy of Sciences.[77] These reports were unanimous in pointing to the growing importance of materials and hence for greater knowledge of their nature and behavior. But, it must be recalled, these pleas were being paralleled by many from other fields of science and engineering in the face of a general

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[77] Julius J.Harwood, “Emergence of the Field and Early Hopes,” Materials Science and Engineering, Rustum Roy, ed., University Park, Pa., (1970) 6.

levelling-off of governmental research support.

The successful orbiting of the Soviet Sputnik in October 1957 gave new incentive for the government to marshall the nation's scientific and engineering resources in a way which had not occurred before, not even in wartime. As the nation came to the realization that its strength lay in its scientific research and engineering knowledge, as well as the educational base to produce the necessary manpower, unprecedented sums of government funds became available for the support of research and education. The field of MSE was one of the chief beneficiaries of this change in the national priorities.

Men at the highest level of government became concerned with the country's requirements for materials. Through its Coordinating Committee on Materials Research and Development (CCMRD), the Federal Council for Science and Technology undertook in 1959 a survey of research needs in the area. This inquiry focused on university research capabilities and on expanding the number of graduate students in the sciences, which had reached a plateau during the years 1948–60. As a result of the CCMRD study, the Federal Council recommended a long-range effort to increase the magnitude of government-sponsored materials research in the universities and to effect a qualitative improvement through the development of more sophisticated research approaches in the field. In its 1960 report, the President's Science Advisory Committee gave its support to the proposals advanced by the Federal Council for Science and Technology.

The Federal Council proposed the following: (a) the establishment of Interdisciplinary Laboratories (IDL) for materials research; (b) improvement of the equipment and facilities of the universities' research capabilities; (c) increasing the production of Ph.D.'s in materials science; (d) enabling individual governmental agencies to carry out the objectives of this policy; and (e) stressing the importance of continuity in the funding on a long-range basis rather than the previous short-term commitments for specific research projects.[78]

The government agency entrusted with the chief responsibility for carrying out these recommendations was ARPA (Advanced Research Projects Agency) of the DoD, Itself organized in 1958 in direct response to the Sputnik impact of the preceding year, ARPA had as its mission the stimulation of innovation in areas of science and technology relevant to national defense. Its task was to prevent the U.S. from being surprised by any more Sputnik-type achievements and to keep America in the forefront of scientific and technological developments, including some whose nature seemed remote from the current activities of the three Armed Services. One of the first programs undertaken by ARPA was the initiation of the IDL program in materials science.[79]

Interest in advancing research in materials science was not confined to the DoD, of course; both NASA and the AEC which had previously provided the

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[78] Reference 77, pp. 7–8.

[79] Robert A.Huggins, "Accomplishments and Prospects of the Interdisciplinary Laboratories," in Problems and Issues of a National Materials Policy, pp. 221–35.

major support continued their programs in materials research.

Three objectives were identified for the IDL program: (a) doubling the output of Ph.D.'s in material science; (b) expanding the capabilities of universities to conduct materials research and expanding the quantity of this research effort; and (c) promoting interdisciplinary mixing in research areas of interest common to various materials-related disciplines.

Interdisciplinary laboratories under this program were established at seventeen universities; twelve were funded by ARPA, three by NASA, and two by the AEC. This was a truly unique program, "aimed at producing a massive upgrading of both quality and quantity in a specific field of basic science of national interest." From its inception in 1960 until the end of fiscal year 1972, ARPA had spent $157.9 million on the IDL program.

There were several significant aspects to the IDL funding program. For one thing, unlike the mission-oriented programs typical of DoD funding, its aim was to improve the academic capabilities for basic research and to expand graduate education. By providing the essential equipment—about one-fifth of ARPA funding went for buildings, laboratory equipment, and central facilities—the DoD through ARPA was laying the foundation for later applied research, sometimes mission-oriented. Furthermore, the detailed technical management of the IDL was handled locally by the university faculties; there was little centralized control from Washington. In addition, although emphasis was placed on the interdisciplinary characteristics of the field, considerable care was taken to avoid injuring the sensibilities of the individual disciplines involved or disturbing the normal departmental organizational structures of academia. Still another unusual element in the program was the provision for long-term contracts or forward funding.

The ARPA program did not provide total support of the IDL's; it featured the concept of core support, that is, only part of the ARPA funds went for operating costs of specific research programs. But ARPA did provide rather liberal funds for building space and research facilities, and so greatly benefited the materials research being financed by grants for specific projects from other governmental agencies. Thus, ARPA funded only about two-fifths of the materials research in academia, with the remaining research support coming from other project-sponsoring agencies and the universities themselves.

The objective of the IDL program in training Ph.D.'s was quickly reached. In 1955, only some 86 Ph.D.'s were granted in the fields of metallurgy and ceramics; by 1965 and 1966, this number had increased to between 160 and 180. But metallurgy and ceramics do not comprise the entire field of MSE by any means. In the group of twelve universities with ARPA/IDL support, the number of Ph.D.'s granted in all materials-related fields went from about 100 in 1960 to between 350 and 360 in each of the years 1967–69. In other words, the IDL program succeeded in more than tripling the number of Ph.D.'s in the materials area. The corresponding effect on quality remains to be assessed, but the indications thusfar look favorable.

The universities were only a part of the total governmental effort to develop MSE. Fueled to a major degree, though not exclusively, by federal expenditures for the aerospace program and other new technologies, industrial research laboratories in metallurgy, polymers, and electronics had become thriving centers for the interdisciplinary "mix" constituting MSE, but focussing for the most part on research needed for short-term applications.

While by 1965 the government had achieved its aim in the IDL program of producing more men with advanced materials-research training, the problem now became one of linking the research performed in the universities with industrial applications. It had to be translated into “hardware.” Of course, this was partially accomplished as the new Ph.D.’s moved into industrial research laboratories, but a closer linkage seemed desirable. In the mid-1960’s, the government began an attempt to connect university research with industrial problems and applications through the ARPA “coupling program.” The issue had been set forth in a report, “Federal Materials Research Program,” prepared in November 1965 by the Coordinating Committee on Materials Research and Development for the Federal Council for Science and Technology. In this, it was pointed out that “frequently knowledge exists in one branch of science and technology, but the application needs occur in another, and the flow of information between the two is not adequate.” The Committee, therefore, recommended “that consideration be given to the problem of insuring that the best available understanding of the behavior of materials be put to use in all phases of their processing, fabrication, and application.”

Although ARPA’s coupling program might not have originated in direct response to the CCMRD recommendation, it was directed to the same end, namely, the application of materials research via a closer relationship between university research and the materials requirements of the Department of Defense, and to stimulate a higher level of applied research activity in academia. Accordingly, ARPA initiated a series of joint contractual relationships for cooperative research in special areas of materials technology between a number of universities and industrial organizations and/or a DoD laboratory.[80]

In the original IDL program, the universities had been the prime contractors, but in the coupling program industrial organizations became the prime contractors, Three such programs were initiated in 1965 and a fourth late in 1966.

In the late 1960’s government support of R & D in all categories, including MSE, began to level off after almost a threefold increase during the years from 1960 to 1966 (almost $2 billion in 1960 to approximately $5.5 billion in 1966), Industrial R & D, which had doubled during the same interval ($7.7 billion in 1960 to $16 billion in 1966) also began levelling off, largely as a result of the decline in federal spending for defense and aerospace programs. This decline was partially due to public disenchantment with the war in Viet Nam, a winding-down of the space effort as the lunar landing became imminent, and the change in fiscal policies induced by a change in the federal administration. Moreover, the rising tide of student discontent with the military, even as a source of funds, made such involvement less attractive to universities. At the same time, growing scrutiny of the DoD budget by Congress made the military increasingly reluctant to sponsor projects which did not have direct connection with defense needs; indeed, “the Mansfield Amendment” made this compulsory.

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[80] Herbert H.Test, “The Materials Research Centers,” Industrial Research (April 1966), pp. 41–47; S.Victor Radcliffe, “Two Decades of Change in Graduate Education in Metallurgy/Materials,” Journal of Metals 21 (May (1969) 29–35.

DoD funding of university research in materials-related basic science was a victim of this change in policy. In 1971 ARPA began withdrawing its support from the IDL program, transferring it to the National Science Foundation (NSF). NSF, on its part, immediately began a review and evaluation of the ARPA/IDL program in order to decide on the proper level of continued support. The funds available were not sufficient to take up the slack left by the DoD withdrawal, especially under the inflationary increase in costs.

The change in the nature and level of governmental funding of research reflected, of course, a change in national goals and priorities. Military and aerospace requirements, which had been a major factor in stimulating government interest in MSE, no longer loomed so large in the popular mind as did questions of the environment, urban problems, and “the quality of life.” The “space race” against the U.S.S.R. had been won when the first Americans landed on the moon (apparently the Russians had withdrawn from this “race” even before this), and the “cold war mentality” had subsided somewhat with the U.S. gradual disengagement from the Vietnamese conflict. There was also the “thawing” of America’s relationship with both the Soviet Union and Red China during President Nixon’s visits to those countries in the Spring of 1972.

Since the underlying stimulus for the first federal spending for MSE was national in objectives and motivations, it is not surprising that changes in these objectives made necessary a re-evaluation of the accomplishments in the materials area. Even before the major outlines of the change in U.S. science policy had made themselves clear, the Committee on Science and Public Policy of the National Academy of Sciences had sensed a change in the situation and therefore commissioned an ad hoc Committee on the Survey of Materials Science and Engineering (COSMAT) to make the present study.

PERSPECTIVES ON MATERIALS SCIENCE AND ENGINEERING

The developments outlined in this chapter show increasing recognition of materials as a field of study which brings together theories, methods, and processes of many separate disciplines. Nevertheless, there is still some doubt as to whether or not MSE has emerged as a distinct professional field. Perhaps this is partly because the IDL program never completely succeeded in providing the close, collaborative interdisciplinary effort which it had envisaged. In too many cases, the disciplinary lines in academia, following compartmented departmental structures, each with its own high degree of autonomy, impeded the full realization of the interdisciplinary potentialities. Communication between physical and chemical scientists sometimes was difficult, and these difficulties were modest in comparison to the communication problem between theoretically-inclined scientists and practically-minded engineers. And even in those instances where the interdisciplinary mixing achieved a fully cooperative and collaborative solution to a problem, this did not mean that a feeling of common professionalism emerged.

At the National Colloquy on the Field of Materials held in 1969 at Pennsylvania State University, two leading members of the field of MSE deplored the fact that materials science had still not achieved professional status, that is, it had not yet become a sociological cluster of peer groups with common concerns and standards. Both Morris Cohen and Rustum Roy recognized this fact. It was observed that materials scientists and engineers did not yet share a common sense of identity; they still thought of themselves as physicists, ceramists, metallurgists, electrical engineers, and the like, not as materials professionals. Roy suggested that the feeling of belonging to a single community of scientists and engineers engaged in the same line of work could only come through the institutionalization of MSE, perhaps through the development of materials-related sections within existing scientific and engineering professional societies and their grouping together across disciplinary boundaries.[81]

Yet, the question of professionalism among those engaged in work on materials may not be a crucial one. The real issue is: what has the emerging field of MSE, with its flexible coupling of disciplines, actually accomplished in the understanding, development, and application of materials?

Here the answer can neither be clear nor definitive. For one thing, the direct governmental support for MSE as a unique field is still fairly recent from the historical point-of-view; hence, the most significant results may not yet be apparent. After all, only in the past several years have the universities begun to turn out Ph.D.'s in materials at an accelerated pace, and they probably have not had time to make their mark in the scientific and engineering world. Moreover, any narration of the accomplishments of MSE is hampered by a lack of complete information. In order, therefore, to look at the successes and failures of MSE, we can refer only to a limited number of cases, some of them occurring before the field had emerged in its present form, some others—only a handful—coming when MSE was finally recognized as a new and different field. We might also be able to project the future usefulness of MSE by attempting to match current needs with the capabilities involved in the nature and methodologies of MSE work.

One of the major industrial achievements of recent times has been the transistor.[82] The transistor was invented before there was any recognition of the uniqueness of MSE as a separate field of science and engineering; MSE cannot claim any credit for originating the transistor, but the transistor can claim some credit for MSE because it focussed attention upon the contributions which the interaction of its component disciplines might make to contemporary society. Interestingly enough, the transistor itself is an outcome of advances in fairly "pure" solid-state physics made by Bardeen and Brattain and Shockley, but it could not have come into useful existence without the inspired semi-empirical development of highly technical zone-refining methods to produce silicon crystals of fantastically high purity and controlled impurities. Moreover, the crystals had to be virtually perfect. Most of the subsequent developments in semiconductors were less dependent upon basic physics than they were upon advances in circuitry, in techniques for microshaping, and in the diffusion of impurity elements to change the local behavior of the semiconductor. No longer did the electrical components have to be separately made and laboriously connected. Every step in this

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[81] "Evaluation and Postscript," Materials Science and Engineering, Rustum Roy, ed. University Park, Pa. (1970) 113–23.
[82] See reference 7, page 1–46.

development needed intimate consultation among scientists and engineers—indeed, the boundary between the two disappeared. The background of all this lay in classical metallurgical studies of crystal growth, diffusion, and oxidation, but it was a new world which required chemical, crystallographic, and mechanical precision far outranking anything previously experienced.

Following the transistor, other devices using semiconductors proliferated. Though previously used in photocells and rectifiers on a small scale, the enhanced theory and sophisticated experience enabled far broader applications. New photoconductors gave birth to a vast array of electrostatic photocopying machines and to devices for seeing in the dark. There are hints that semiconducting surfaces may substitute for the conventional silver-based chemically-developed photographic film, itself in its development a marvel of interaction between physical and chemical research and purposeful industrial development.

The laser, so pregnant with possibilities in many fields, is an example of a discovery prompted by intellectual curiosity being rapidly developed by purposeful engineering, both needing and yielding physical insight at every stage.

A much earlier example was the development of hard and soft magnetic materials. The introduction of silicon iron for transformer cores in the early 1900's had a spectacular effect in cutting power losses and in electrical distribution systems.[83,84] As the domain theory of ferromagnetism was developed, even softer materials appeared for communication devices, and at the other extreme, there came magnets of strength and stability orders-of-magnitude better than the older steel or lodestone magnets.

The factor most responsible for the almost explosive change of knowledge and technical capacity in these materials-related areas is the conscious interaction among scientists and engineers. In all of these cases, there was some background of existing knowledge of the materials (sometimes acquired in the academic physics laboratory), but the large-scale applications arose from specifically-directed activity based on new theory and requiring constantly new techniques for realization. In the first half of the 20th century, the electrical industry made or inspired almost all the new materials other than steel.

A recent example of a spectacularly new use of old material is that of plastic composites in ablative nose cones, without which space vehicles could not safely re-enter the earth's atmosphere. The first search for materials to dissipate the frictional heat was directed toward refractory metals and ceramics; the solution came unexpectedly from plastics, whose decomposition absorbed heat and left behind a continuously renewable porous, insulating, heat-radiating layer of char. Charring had previously been regarded as a thoroughly undesirable characteristic of organic polymeric materials. Now the principle is being applied to other high-temperature insulating problems, such as for piping.

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[83] Robert Hadfield, Metallurgy and Its Influence on Modern Progress, Chapman and Hall, London (1925). On transformer iron see especially pp. 125–139.

[84] J.H.Bechtold and G.W.Wiener, "The History of Soft-Magnetic Materials," Sorby Centennial Symposium, C.S.Smith, ed., pp. 501–518. (See ref. 50.)

New applications for a material can rarely be anticipated for they depend on nonmaterial factors. The properties of any kind of material embody the basic nature of matter, which underlies all things no less than do the laws of gravitation and relativity, but in the present stage of knowledge, real materials combine the basic principles in a way not often predictable. The transfer and development of materials found in a given setting to be appropriate for another is more common than designing them from first principles. Transfer instead of invention is even more frequent in technology than in science. For example, titanium metallurgy was developed intensively with military aircraft applications in mind (benefiting, incidentally, from the experience with zirconium which had proved so useful in nuclear reactors and which had many metallurgical similarities with titanium); as a result, titanium was ready for the supersonic transport when it was cancelled. However there is little doubt that the combination of lightness, strength (particularly at high temperatures) and corrosion resistance of titanium will find numerous applications, particularly since its ores are abundant in the earth’s crust and it will certainly become cheaper as its presently-difficult technology is mastered.

The development of composite materials provides another example of payoff in MSE, and also of some beneficial spillover from military to civilian technology, DoD subsidized much research on glass- and other fiber-reinforced plastics of high strength, low weight, and high modulus of elasticity. This began with ballistic missile cases and with structural components of aircraft in mind, and the success in the military applications stimulated the civilian economy for these materials in boats, truck cabs, trailer bodies, geodetic structures, fishing poles, pipe, battery cases, storage tanks, and the like. Such high-strength, light-weight structural materials may some day replace steel and concrete in the multitude of everyday applications.

Perhaps the developments in MSE most familiar to the civilian population are those involving plastics. After all, many of the more sophisticated materials, such as the transistor, although used in everyday devices, are buried inside a “black box.” What the public sees, feels, and becomes conscious of are the outsides of the “black boxes,” which are often made of plastic. Plastics in their many forms, stiff or flexible, transparent or opaque, filmy, fibrous, or massive have found their way into every room of the house (especially the kitchen), replacing older materials, usually giving cheaper objects, but perhaps less fragile, more flexible, and often more colorful if not more richly decorative than those that they replaced. The variability of the chemistry of the underlying polymeric molecule and the versatility of the fabricating techniques enable materials to be tailored to almost any specific needs.

Newly-developed materials enable new things to be done, but they also may do the old ones better or more cheaply. The competition gives life to old industries. Plastics substitute for leather, wood, ceramics, and metal in thousands of applications. Electrical transmission cables have always been covered with insulation of some kind; now synthetic polyethylene can not only be applied more easily than the older coatings, but its electrical properties and its resistance to aging are far superior.

It is in this area of substitutions that the next phase of MSE may be most visible, for it ties in with concern over the exhaustion of certain natural resources. Substitutions will enable us to make use of more abundant raw materials than those which are less abundant. However, it must be pointed out that substitution cannot be applied in an unthinking manner, for both short-range and long-range considerations are involved. If more energy is used in providing a substitute or in recycling, this may entail an overall retrogression of environmental quality. The entire complex of materials resources must be considered; we must protect the materials resources of future generations as well as our own. Perhaps the chief emphasis should be to develop materials which can be recovered and re-used. The refuse of a city is a valuable, if dilute, ore body, whose exploitation is a challenge to MSE.

Another way to conserve natural resources is to adopt more efficient designs and to employ materials that are stronger, lighter, and more resistant to decay by corrosion. The interdependent nature of technologies and resources would seem to require the integration of our efforts in MSE into the broader goals of national policy.

However, the story of the development of MSE is not wholly one of successes. There have been failures as well as triumphs. Most of the failures, involving blind alleys of research which have not resulted in applications, go unreported; in the world of science and technology, as in the world of sports, the attention is focused on the "winners." On the other hand, much can be learned from experiences that did not produce good results, and indeed, the history of metallurgy during the past two centuries contains many instances of knowledge gained by studying failures in processing and in applications. Yet, by and large, it is the successes—or potential successes—of MSE which achieve publicity and which attract the investment of large sums, both governmental and private, into further research in the field. There are inevitably hazards surrounding the introduction of new materials, especially when there is inadequate time for testing them under service conditions. Indeed, it is unlikely that promoters can fully anticipate either the difficulties or the successes. Initial enthusiasm for new materials has almost always been followed by a period of disenchantment, and this in turn by a period of slower, sound growth. This was true with Bessemer and his new steel process; aluminum, at first a miracle metal struggled for many years before it was accepted by the engineering world on the basis of slowly-gained experience; and more recently titanium failed to meet many of the promises of its proponents, before finding its proper, useful niche.

There has been one particularly-publicized "failure" of MSE. It was the inability of the Rolls-Royce Company to develop highly-promising new composite carbon-fiber materials to the stage of service reliability needed for the engines in the Lockheed Tristar which forced the Rolls-Royce Company into bankruptcy and threatened one of America's leading aerospace manufacturers with financial ruin. The implications of this event were enormous, both internationally as well as domestically. Grave issues of public policy arose when the Lockheed Corporation asked the federal government for funds to sustain its operations; relations between the U.K. and the U.S. were embittered; and a serious blow was struck at the British economy. Some ascribed the inability of Rolls-Royce to meet its goals to managerial shortcomings; others blamed the deficiencies of materials scientists and engineers, who themselves still quarrel over whose fault it was. Others claim that too great reliance was placed upon the promise of a single materials development—albeit a highly promising one—without the precaution of following up alternative technologies to fall back on in case of failure. Still others maintained that the scientists and engineers involved were endeavoring with inadequate service testing to make too great a leap beyond the existing state of the art.

The episode will probably continue to be a source of discussion and argument for many years. Perhaps no single explanation is correct; perhaps many contributing errors of judgment interacted to yield the final debacle. The entire episode has had a sobering effect upon over-enthusiastic proponents of MSE.

The Rolls-Royce episode reminds us that MSE is not an American monopoly, but like all science and technology, is international in scope. The British practitioners of MSE have also had their share of successes—indeed, most of the earlier steps toward both the science and the engineering of materials took place in England, and a disproportionate fraction of the leading scientists in the field are in the U.K. today. There is an international community of materials scientists and engineers, and it happens that many of the leaders in the materials field in the U.S. today are of foreign birth and education.

The international character of MSE might also be a matter of foreign-policy concern for the U.S., not only in regard to the availability of resources and strategic materials on a global scale, but also in terms of international competition and cooperation in science and technology.

The significance of science and engineering in contemporary life involves more than the competition among nations. It is basic to the quality of life within a nation for present and future generations. The increasing emphasis upon the ecological consequences of contemporary technologies provides another challenge to MSE. Through the development of substitute materials and the creation of new ones, MSE might be a means of insuring the continuation of a highly industrialized society and the extension of its benefits throughout the earth. We must produce and utilize materials in such a way that an ecological balance between social man and his physical environment can be maintained. In this, of course, all fields of science and engineering are encompassed and are dependent upon economic, social, and political changes. While it is true that science and technology have created some of our current problems, many of these are socio-political in origin and antedate the birth of our present industrial civilization. The solution of those problems cannot be resolved by a moratorium on science or by endeavoring to turn back the technological clock. We will need more science and technology leading to a better understanding of social, environmental, and resource interactions. In all this, MSE must certainly play a significant role. At least, MSE provides a powerful example for study of an multidisciplinary effort in a combined academic-governmental-industrial endeavor.

The most advanced MSE has heretofore been applied chiefly to the highly-sophisticated requirements of military, aerospace, nuclear energy, and electronics. Now it must be expanded to include civilian programs, the development of new materials, and new methods of processing the old ones. Will the cooperation of academic-governmental-industrial efforts be as capable of producing results in the civilian sector?

While, as Dr. Walter Hibbard has stated, MSE might be of relatively little assistance in solving contemporary needs in housing, which he believes are capable of solution by existing technology and by certain economic, social, political changes, there are many areas of public concern which will require the attention of the materials community. MSE could exemplify the newly-awakened consciousness of the scientific-technical community toward social concerns, and it is in the context of this new challenge to scientists and engineers that the present report on MSE is undertaken. The national goals and priorities are changing, and MSE itself must adjust in order to meet the new opportunities which society poses for it—and for all of science and technology.

Finally, the COSMAT study is based upon a philosophical presupposition, which may be in some public disrepute today among those who manifest interest in the occult and who place emphasis on emotional and romantic means of solving human problems. COSMAT relies on the proposition that science and technology represent rational means of coping with the human condition and on the further proposition that MSE can make a great contribution, if wisely applied and utilized, to that end.

In retrospect, it can now be discerned that the various strands of MSE took form quite separately—the discovery and development of many different kinds of materials, the approaches of scientists, engineers, and entrepreneurs with quite different aims and methods, the individual specialized techniques for materials fabrication and utilization, and, by no means least, the educational, industrial, and social organization to weave together all of these strands.

Now that interrelationship of these things has been recognized, one can perceive within MSE a pattern of approach toward complex problems that may be transferable to other areas. It uses every bit of knowledge obtained by rigorous analytical thinking, but it applies this to real situations that have arisen as a result of a long and unique history. Brilliant successes in science for the last four centuries have come from the analytical approach, and the resulting expansion of knowledge has been enormous. But the mere aggregation of precise parts does not make an effective whole. The recent concern with ecology illustrates this in another domain. The advances of molecular biology have prepared the way for a new study of the nature of organisms, their evolution, their individual growth and morphology, and is beginning to revitalize the older fields of nature study as a whole. At the present stage of history, we have such extensive knowledge of the behavior of atoms in small groups that we are not likely to be in for any great surprises in that regime; on the other hand, scientists are only just beginning to be aware of the great richness of the phenomena arising from the larger aggregation of atoms, Perhaps the complex interactions in MSE are already pointing toward a richer science which may eventually, in an analogous fashion but on a higher level, even deal with interactions between the sciences and society. At least some practitioners in MSE see in the behavior of their materials on an atomic level a pattern of structures and structural changes which, on an ever-larger scale and with changing units, form overall patterns of higher and higher levels of aggregation encompassing more and more functions. One can also find in materials a suggestive metaphor that may be applicable to many other areas—a nucleus of a new event appearing before its environment is ready for such a change will not persist. In other words, anything whatever takes meaning only by interaction with things external to itself, and that will surely be true for MSE.

CHAPTER 2
THE CONTEMPORARY MATERIALS SCENE*

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* This chapter draws on the work of several of the COSMAT Panels, but particularly on that of the Data and Information Panel and its chairman, Robert I.Jaffee.

CHAPTER 2

THE CONTEMPORARY MATERIALS SCENE

THE NATURE OF MATERIALS

This report is concerned primarily with industrial materials that are used to make things—products like machines, devices and structures. Such materials are ubiquitous, so pervasive we often take them for granted. Yet they play a central role in much of our daily lives, in practically all manufacturing industries, and in much research and development in the physical and engineering sciences. Materials have a generality comparable to that of energy and information, and the three together comprise virtually all technology.

Materials are basic to manufacturing and service technologies, to national security, and to national and international economies. The housewife has seen her kitchen transformed by progress in materials: vinyl polymers in flooring; stainless steel in sinks; Pyroceram and Teflon in cookware. The ordinary telephone contains in its not-so-ordinary components 42 of the 92 naturally-occurring elements. Polyethylene, an outstanding insulator for radar equipment, is but one of myriad materials vital to national defense. By one of several possible reckonings, production and forming of materials account for some 20% of the nation's Gross National Product, but the number is deceptive; without materials we would have no Gross National Product.

Man tends to be conscious of products and what he can do with them, but to take the materials in those products for granted. Nylon is known far better in stockings than as the polyamide engineering material used to make small parts for automobiles. The transistor is known far better as an electronic device, or as a pocket-size radio, than is the semiconducting material used in the device and its many relatives.

Some materials produce effects far out of proportion to their cost or extent of use in a given application. Synthetic fibers, in the form of easy-care clothing, have worked startling changes in the lives of housewives. Certain phosphor crystals, products of years of research on materials that emit light when bombarded by electrons, provide color-television pictures at a cost of less than 0.5% of the manufacturing cost of the set.

The properties of specific materials often determine whether a product will work or not. In manned space flight, ablative materials of modest cost are essential to the performance of the heat shield on atmospheric reentry vehicles. New or sharply improved materials are critical to progress in energy generation and distribution. At the other extreme are home-building materials, whose properties, though important, need not be markedly improved to meet society's goals in housing.

Materials commonly serve a range of technologies and tend to be less proprietary than are the products made of them. Materials, as a result, are likely to offer more fruitful ground for research and development, including cooperative research and development, than are specific products. One example is fiberglass, which can be used for making pleasure boats, housing construction, and automobile bodies. Another example is certain "textured" materials, polycrystalline structures in which the alignment of neighboring crystals is determined by the processing steps employed. The ability thus to control crystal orientation grew out of research by physicists, metallurgists, and even mathematicians. The resulting improvements in properties are proving useful in a widening spectrum of applications. They include soft magnetic alloys for memory devices, oriented steels for transformers, high-elasticity phosphor bronze for electrical connectors, and steel sheet for automobile fenders, appliance housings and other parts formed by deep drawing.

THE NATURE OF MATERIALS SCIENCE AND ENGINEERING

Materials science and engineering is a multidisciplinary activity that has emerged in recognizable form only during the past two decades. More specifically:

> 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 uses.

The multidisciplinary character of materials science and engineering is evident in the educational backgrounds of the half-million scientists and engineers who, to varying extents, are working in the field. Only about 50,000 of them hold materials-designated degrees*; the rest are largely chemists, physicists, and nonmaterials-designated engineers. Many of these professionals still identify with their original disciplines rather than with the materials community. They are served by some 35 national societies and often must belong to several to cover their professional and technical needs. This situation is changing, if slowly. One recent indication was the formation of the Federation of Materials Societies in 1972. Of the 17 broadly-based societies invited to join, nine had done so by October, 1973.

Materials are exceptionally diverse. Correspondingly, the scope of materials science and engineering spans metals, ceramics, semiconductors, dielectrics, glasses, polymers, and natural substances like wood, fibers,

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* We define a "materials-designated degree" as one containing in its title the name of a material or a material process or the word "materials." Examples include metallurgy, ceramics, polymer science or engineering, welding engineering, and materials science or engineering. Thus far, virtually all materials-designated degrees are in metallurgy or ceramics.

sand, and stone. For COSMAT purposes, we exclude certain substances that in other contexts might be called "materials." Typical of these are food, drugs, water, and fossil fuels. Materials as we define them have come increasingly to be classified by their function as well as by their nature; hence biomedical materials, electronic materials, structural materials. This blurring of the traditional classifications reflects in part our growing if imperfect ability to custom-make materials for the specific functions required of them.

MATERIALS IN THE U.S. ECONOMY

The United States, with about 6 percent of the world's population, consumes from 25 to 50 percent of the world's output of resources. The American people have become accustomed to a great variety and quantity of material goods from a resource base which may be diminishing. Private industry, our society's instrument for providing these material goods, has evolved a remarkably successful producing system to keep pace with ever growing product demand. World trade and improved technology are both parts of this system. Our country must export products to pay for the raw materials imports. And it is through continued scientific and technological progress to improve the efficiency of materials use that we compete successfully in world product markets.

About 20 percent of our Gross National Product originates in the extraction, refining, processing, and forming of materials into finished goods other than food and fuel. All materials pass through a number of stages in their economic utilization. At each stage, value is added and cost is incurred to pay for energy, production and research, manpower, administration, and finally disposal and recycling costs. The primary instrument generally used in our society for implementing this utilization of materials is private industry. Competing in the market place under ground rules established by society through its governmental bodies, private industry attempts to minimize the cost of materials utilization in order to produce quality goods that satisfy its customers, and to provide a reasonable return on investment to its owners.

The consumption of basic materials in the U.S. has been growing steadily (Table 2.1), along with the population and standard of living. Another measure of the impact of materials on the economy is manufacturing employment related to materials, which was just over 16 million in 1970, or about 21% of total employment.

A third measure of the importance of materials in the nation is their contribution to the National Income or to the Gross National Product[1]. Table 2.2 indicates the main industrial categories contributing to the former and

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[1] The National Income and Product Accounts of the United States, 1929–1965. Office of Business Economics, U.S. Department of Commerce, U.S. Government Printing Office, Washington, B.C., 1966.

TABLE 2.1 Consumption of Selecteda Basic Materials in the U.S. (Millions of Tons)

	1950[b]	1971[b]		1950[b]	1971[b]
Aluminum	1.3	5.5	Clays	39.5	55.1
Calcium	N.A.	90.3	Gypsum	11.4	15.7
Copper	2.0	2.4	Pumice	0.7	3.5
Iron	94.5	122.2	Sand and gravel	370.9	987.7
Lead	1.4	1.3	Stone, crushed	N.A.	823.0
Magnesium	N.A.	1.1	Stone, dimension	N.A.	1.8
Manganese	1.1	1.2	Talc	0.6	1.1
Phosphorus	1.7	5.1	…		
Potassium	1.2	4.5	Agricultural fibers	N.A.	2.1
Sodium	N.A.	19.0	Forest products	N.A.	237.0
Sulfur	6.8	12.4	Plastics	1.0	10.0
Zinc	1.1	1.2			

[a] Commodities used in excess of 1 million tons in 1971. Totals include government stockpiling, industry stocks, and exports. Foods and fuels are not included.

[b] 1950 actual; 1971 estimated.

Source: First Annual Report of the Secretary of the Interior under the Mining and Minerals Policy Act of 1970, March 1972. Figures for agricultural fibers, forest products, and plastics compiled by COSMAT from various sources.

TABLE 2.2 Distribution of National Income[a] of the United States by Industry Category–1965

Category	Percentage Share
Agriculture, Forestry, and Fisheries	3.76
Mining	1.15
Contract Construction	5.06
Manufacturing	30.48
Transportation	4.10
Communication	1.99
Electric, Gas, and Sanitary Services	2.08
Wholesale and Retail Trade	14.95
Finance, Insurance, and Real Estate	10.91
Services	11.27
Government and Government Enterprises	13.46
Rest of the World	0.76
	99.97

National Income for 1965=$559,020 million
(all industry total)
Gross National Product for 1965=$681,207 million

[a] Data computed from statistical tables in The National Income and Product Accounts for the United States, 1929–1965, Office of Business Economics U.S. Department of Commerce, U.S. Government Printing Office, Washington, D.C., 1966.

their distribution in 1965. The two categories of Mining and Manufacturing relate primarily to materials, and it can be seen that they contribute some 31.6% to the National Income. An additional amount arises from the 3.76% represented by Agriculture, Forestry,and Fisheries. The specific contribution of materials in the above categories is strongly concentrated in particular subcategories. Table 2.3 and the corresponding Table 2.4 for GNP in 1971 show the distribution among the principal subcategories; those relating primarily to materials are metal-mining, mining and quarrying of nonmetallic materials, paper and allied products, rubber and miscellaneous plastic products, leather and leather products, lumber and wood products, stone, clay and glass products, primary metal industries, and fabricated metal products. These operations on materials account for perhaps one-tenth of the nation's consumption of fuels.

While the above groups alone constitute a significant portion—some 9%–of the National Income, there are additional and major materials contributions in most of the other manufacturing subcategories which cannot be separated in terms of their share of the National Income. The difficulty stems from the nature of this measure of economic activity, which is the aggregate earnings of labor and property that arise in the current production of goods and services by the nation's economy, i.e. the total factor costs of the goods and services produced by the economy.

An alternative economic approach that might be adapted to give better insight into the contributions of materials is the modeling of the structure of an economic system by "input-output" or "inter-industry" analysis originated by W.W.Leontief of Harvard University. The technique describes the production process in a given industry in terms of a detailed accounting of its purchases from other industries, i.e. its inputs of raw and semifinished materials, components, and services. The complete record of inter-industry transactions described in this way within the entire economy is displayed as a square-matrix or input-output table. This method has been used to identify the primary materials component of the economy in the sense discussed above, but only partially separates materials in the various manufacturing areas. In any case, the analysis is still concerned with economic value, whereas many of the questions and problems associated with materials flow are concerned with mass or volume rather than value alone.

Despite these limitations for the present purpose, some results of particular interest concerning materials have arisen from the application of the technique carried out by Carter[2] in which structural changes in the U.S. economy arising from changes in technology were analyzed by comparing input-output tables prepared for two different years–1947 and 1958. The results show strikingly the relative increase over this period in "nonmaterial" or "general" inputs (these include energy, communications, trade, packaging, maintenance construction, real estate, finance, insurance and other services, printing and publishing, business machines and information technologies) that are largely balanced by relative decreases in the input of

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[2] A.P.Carter, Structural Changes in the U.S. Economy, Harvard University Press, Cambridge, Mass., 1970.

TABLE 2.3 Distribution of National Income of the United States within Selected Industry Categories–1965

A.	MINING CATEGORY ($6,432 million=1.15% National Income)		
	SUBCATEGORY	SHARE OF CATEGORY (PERCENTAGE)	
	Metal Mining	15.93 (0.18)[a]	
	Coal Mining	21.16 (0.24)	
	Crude Petroleum and Natural Gas	43.14 (0.50)	
	Mining and Quarrying of Nonmetallic Materials	19.76 (0.23)	
		100.0	
B.	MANUFACTURING CATEGORY ($170,408 million=30.48% National Income)		
	SUBCATEGORY	SHARE OF CATEGORY (PERCENTAGE)	
	Nondurable Goods:		
	Food and Kindred Products	8.50 (2.59)	
	Tobacco Manufacturers	0.70 (0.21)	
	Textile Mill Products	3.44 (1.05)	
	Apparel and Other Fabricated Textile Products	3.85 (1.17)	
	Paper and Allied Products	3.36 (1.02)	
	Printing, Publishing, and Allied Industries	5.06 (1.54)	
	Chemicals and Allied Products	7.24 (2.20)	
	Petroleum Refining and Related Industries	2.97 (0.71)	
	Rubber and Miscellaneous Plastic Products	2.34 (0.71)	
	Leather and Leather Products	1.07 (0.33)	
			38.53 (11.74)
	Durable Goods:		
	Lumber and Wood Products, except Furniture	2.42 (0.74)	
	Furniture and Fixtures	1.67 (0.51)	
	Stone, Clay, and Glass Products	3.40 (1.04)	
	Primary Metal Industries	8.65 (2.64)	
	Fabricated Metal Products	6.65 (2.03)	
	Machinery, except Electrical	10.77 (3.82)	
	Electrical Machinery	8.34 (2.54)	
	Transportation Equipment and Ordnance, except Motor Vehicles	6.78 (2.07)	
	Motor Vehicles and Motor Vehicle Equipment	8.53 (2.60)	
	Instruments	2.58 (0.78)	
	Miscellaneous Manufacturing Industries	1.68 (0.51)	
			61.47 (18.74)
			100.0

[a] Figures in parentheses indicate the subcategory share as a percentage of the total National Income.

TABLE 2.4 Selected Industry Components of the Gross National Product (1971) (1971 GNP=$1,050,356 million)

	Millions	% of GNP
Metal Mining	$ 1,290	0.12
Mining and Quarrying of Nonmetallic Metals	1,654	0.16
Stone, Clay, and Glass Products	8,710	0.83
Primary Metal Industries	18,923	1.80
Fabricated Metal Products	16,427	1.56
Machinery, except Electrical	26,066	2.48
Electrical Machinery	22,388	2.13
Transportation Equipment, except Motor Vehicles	14,582	1.39
Motor Vehicles and Motor Vehicle Equipment	22,824	2.17
Instruments	6,456	0.61
Miscellaneous Manufacturing Industries	4,144	0.39
Chemicals and Allied Products	20,387	1.94
Rubber and Miscellaneous Plastic Products	7,371	0.70
Lumber and Wood Products, except Furniture	6,395	0.61
Furniture and Fixtures	3,984	0.38
Paper and Allied Products	9,357	0.89
Textile Mill Products	8,234	0.78
Apparel and Other Fabricated Textile Products	9,293	0.88
Leather and Leather Products	2,219	0.21
	$210,704	20.03

Source: U.S. Department of Commerce

materials and semifinished goods. Thus, the iron and steel sectors declined relatively some 27% (despite substantial growth in absolute terms), reflecting substitution by aluminum and plastics together with design changes to reduce the total amount of metal used by taking advantage of the improvements developed in steel properties and performance. A relative decline of 23% in nonferrous metals is the balance resulting from increased use of aluminum and the decreased use of other nonferrous metals. In addition to the relative decline of the materials inputs (which basically represents a more efficient use of materials), Carter shows that

> "the classical dominance of single kinds of material—metals, stone, clay and glass, wood, natural fibers, rubber, leather, plastics and so on—in each kind of production has given way by 1958 to increasing diversification of the bill of materials consumed by each industry. This development comes from interplay between keenly competitive refinement in the qualities of material and design backward from end-use specifications."

These interpretations of the influence of technological change appear to be in keeping with the results of a different type of economic analysis involving materials flows reported recently for an earlier period by Gold.[3] For a variety of manufacturing industries, the influence of technological innovation over the 40-year period through 1939 was found not to be directly detectable in the proportioning among deflated unit costs (materials, wages, and salaries, and other costs plus profits) over this long-time series. The horizontal trend exhibited by the data (for steel-mill products in Figure 2.1) shows that the proportions of the cost components have remained approximately constant, despite the introduction of specific technological advances at known points in time. These observations do not mean an absence of benefits from technological progress, but rather that such progress was so pervasive in the economy at large that advances in a given industry simply maintained its competitive position with other industries. On this basis, the innovations have directly benefited consumers of a given industry's products (in effect, much of the economic gain has been passed on to them), but have not provided much competitive advantage beyond that of effective survival in a given market.

The preceding discussion has indicated some of the principal economic measures and models for materials flows. An important contribution in relating these economic factors to the associated bulk flows is provided by the U.S. Bureau of Mines in an Analysis of the supply-demand relationships for mineral resources and commodities. In their 1970 report[4] which covers

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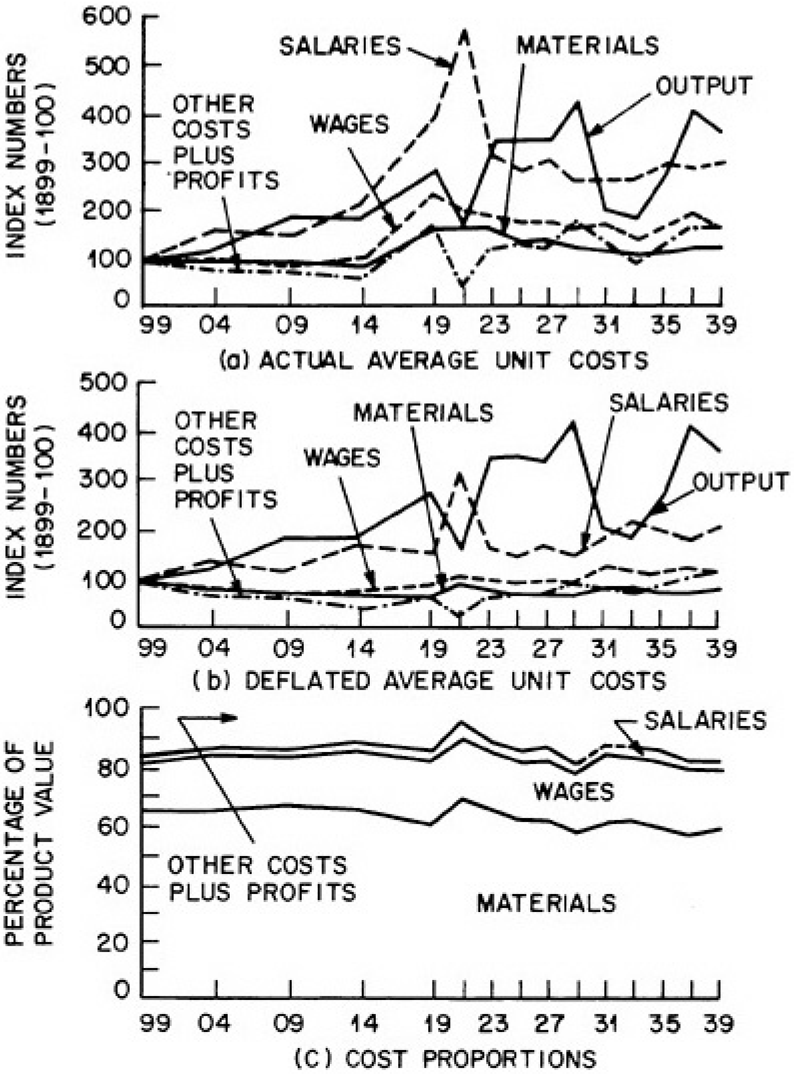
[3] B.Gold, Exploration in Managerial Economics—Productivity, Costs, Technology and Growth, MacMillan Company, London, 1971.

[4] Mineral Facts and Problems, Fourth Edition, Bureau of Mines Bulletin No. 650, U.S. Department of the Interior, U.S. Government Printing Office, Washington, D.C., 1970.

FIGURE 2.1
STEEL MILL PRODUCTS. PHYSICAL OUTPUT, ACTUAL AND DEFLATED AVERAGE UNIT COSTS AND COST PROPORTIONS, 1899–1939. (AFTER GOLD)



88 commodities, the emphasis of the analysis was broadened from an essentially “supply” orientation to include intermediate forms and end-uses. This change is especially important for the problem of predicting the evolution of future demand—such as is done in the analyses to the year 2000–but is also critical for the monitoring of materials flows at the present time. It, and the subsequent reports from the Secretary of U.S. Interior, provide specific information on a large group of resources that supplement still broader discussions of resource adequacy, such as those presented by Landsberg[5] and the National Academy of Sciences study, Resources and Man[6].

An example of the supply-demand data is shown for copper in Figure 2.2. The significant features of the data are that (a) the flow at any stage is expressed in terms of the mass of elemental metal, whether or not the commodity exists in that form at that stage, (b) the world sources of the metal that contribute to the total U.S. supply are delineated by country of origin, and (c) the resulting U.S. supply is broken down into industry stocks and exports as well as into the proportions going into specific industries (identified in terms of the Standard Industrial Classification developed by the U.S. Department of Commerce).

Data of the type provided by the Bureau of Mines analyses should permit the setting up of a bulk-flow model involving the 88 different commodities as elemental materials, although the present information does not appear to be sufficiently comprehensive with respect to the industrial classifications used. Thus, a square-matrix analog of the inter-industry type would be less complete and interpretable than for the economic model developed by Leontief. Furthermore, it is important to be able to identify the actual bulk flow at various stages rather than simply the elemental flow, and knowledge is also needed relative to the residuals developed at all stages as well as the extent of recycling and final disposal. Reliable statistical information on residuals in the form of both new scrap material (resulting during manufacture and processing stages) and old scrap (from the discarded unit or component after use by the consumer) is now becoming available through the efforts of various federal agencies and interested trade associations. However, such data are still incomplete, especially with respect to old scrap and its long-term accumulation from past activity. Furthermore, information on nonsolid discharges is particularly limited.

In the preceding discussions, the question of competition between variants of the same material (e.g. different alloys) and between different materials (e.g., plastics and metals) is visible as a significant factor in determining changes in materials flow with time. Such competition is one

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[5] H.H.Landsberg, Natural Resources for U.S. Government, Resources for for the Future, Inc., Johns Hopkins Press, Baltimore, 1964.

[6] Resources and Man (Report of the Committee on Resources and Man, Chairman, P.Cloud, National Academy of Sciences) W.H.Freeman and Co., San Francisco, 1969.

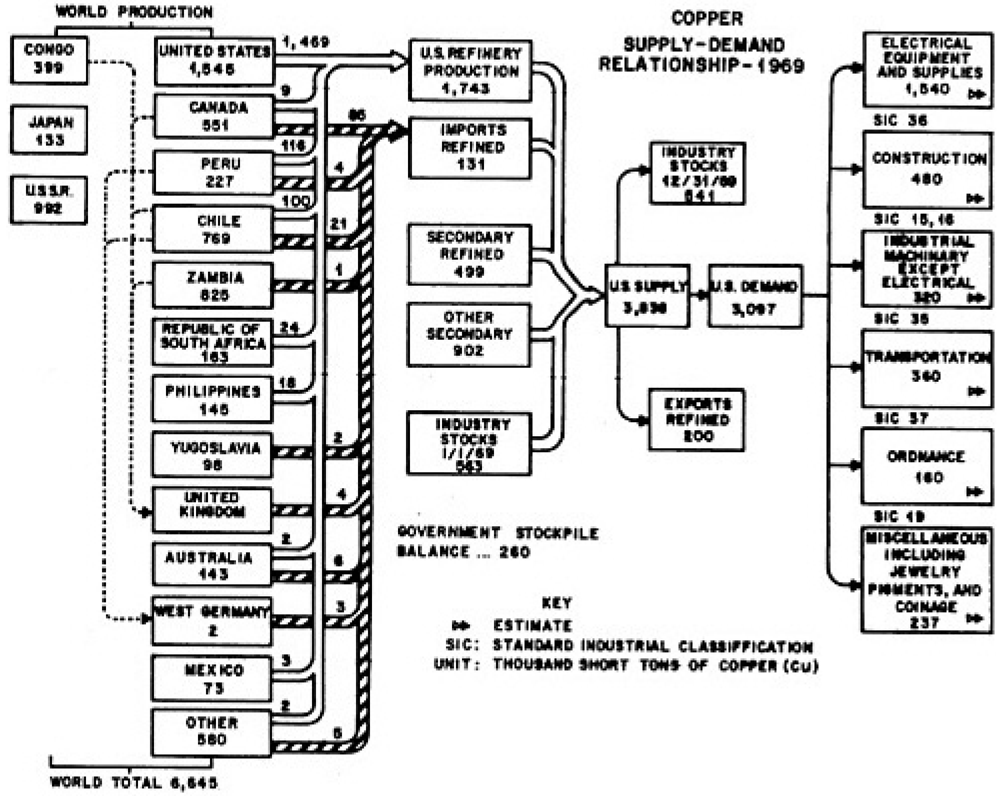

FIGURE 2.2
SUPPLY-DEMAND RELATIONSHIP FOR COPPER IN 1969 (U.S. BUREAU OF MINES)

aspect of the broader concept of substitution, which has emerged from an earlier restricted connotation of the use of an inferior material in a given application for a superior one that is limited in availability or higher in cost. Previously-used derogatory terms such as “cheap plastic” or “tinny” are indicative of that earlier meaning. However, perhaps one of the most important aspects of the revolution in the diversity of available technological materials is that the improved understanding of the science and technology of materials now offers a better basis for developing options in providing materials for specific needs, i.e. for providing substitutes that match or improve upon the performance of other materials. The continuing demand for materials in the future and the decreasing availability of specific materials as nonrenewable resources are consumed or become uneconomic, together with the restrictions imposed by the need to control environmental quality, will require a vigorous extension of this understanding of substitutions in the future. It may be even more useful to take into account the broadest interpretation of substitution. Thus, one should consider not only the materials-flow implications of substituting one material for another in the same class (e.g. aluminum for copper in electrical conductors) or for one in another class (e.g. fiberglass for ceramics in sewer pipes), but also of substituting an entire technology (e.g. transport by automobile rather than by horse or by aircraft rather than ship, electric power from nuclear fission or fusion rather than from fossil fuel).

Despite the shortcomings in the range of quantitative data available on materials flows in the United States, it appears that there is already sufficient information on past and present flows to merit assembling into an initial framework. A desirable first step in this direction has already been taken by the U.S. Bureau of Mines in the development of a computer-storage system for information on resource reserves. The expansion of such inventories to include the supply-demand data of the type in Figure 2.2, together with associated information on residuals and recycling, would be an appropriate next step. However, such inventories are essentially static models and the nature of the problems associated with our dynamic society require at least the exploration of possible dynamic models that would highlight the consequences of the complex interactions involved in materials flows on a national or international scale. One such approach would be to simplify the problem by restricting it to a consideration of mass flows between industrial sectors in an analog of the Leontief system. Here, the influence of changing technical or market opportunities or social demands would be inserted indirectly through changes in the output requirements of specific industries. This technique would permit the exploration of mathematical models for technological forecasting relating to future materials demands, such as that suggested by Fisher and Pry[7]. Also, with the development of appropriate input data, this method should be adaptable to accommodate more completely the full variety of flows operative in the total materials cycle.

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[7] J.C.Fisher and R.H.Pry, “A Simple Substitution Model of Technological Change,” Report 70-C-215, General Electric Research Center, Schenectady, New York, 1970.

An alternative approach is the even more ambitious and controversial systems-dynamics analysis developed by Meadows et al[8] on the basis of the global model suggested by J.Forrester. Here, materials enter the model principally as natural resources and a component of pollution—which are two of the five basic factors (the other three being population, agricultural production, and industrial production) that are interacted and are considered in this model to place limits on ultimate growth on the planet. A major issue in the debate as to the validity of the conclusions reached from this global model—whether one considers the model predictive or, as the authors propose, only indicative of behavior modes to be expected if present trends continue—has been the reliability of the data-base available at the present time. Despite such controversy over the current use of the model, the approach itself does appear to offer an important new research tool for examining the interaction of major factors at play in continuing national or global development. The further exploration of this technique to study the dynamics of natural resource utilization, as has already been initiated, merits careful attention in order to improve man’s understanding of the changing characteristics of materials flows.

THE MATERIALS CYCLE AND THE ROLE OF MATERIALS SCIENCE AND ENGINEERING

All materials move in a “total materials cycle” (Frontispiece) which in this report we will simply call the “materials cycle.” From the earth and its atmosphere, man takes ores, hydrocarbons, wood, oxygen, and other substances in crude form and extracts, refines, purifies, and converts them into simple metals, chemicals, and other basic raw materials. He modifies these raw materials to alloys, ceramics, electronic materials, polymers, composites, and other compositions to meet performance requirements; from the modified materials he makes shapes or parts for assembly into products. The product, when its useful life is ended, returns to the earth or the atmosphere as waste. Or it may be dismantled to recover basic materials that reenter the cycle.

The materials cycle is a global system whose operation includes strong three-way interactions among materials, the environment, and energy supply and demand. The condition of the environment depends in large degree on how carefully man moves materials through the cycle, at each stage of which impacts occur. Materials traversing the cycle may represent an investment of energy in the sense that the energy expended to extract a metal from ore, for example, need not be expended again if the metal is recycled. Thus, a pound of usable iron can be recovered from scrap at about 20% of the “energy cost” of extracting a pound or iron from ore. For copper the figure is about 5%, for magnesium about 1.5%.

Materials scientists and engineers work most commonly in that part of the materials cycle which extends from raw materials through dismantling

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[8] D.H.Meadows, D.L.Meadows, J.Rander and W.Behrens, The Limits to Growth, Potomac Associates, Universe Books, New York,1972.

and recycling of basic materials. Events in this (or any other) area typically will have repercussions elsewhere in the cycle or system. Research and development, therefore, can open new and sometimes surprising paths around the cycle with concomitant effects on energy and the environment. The development of a magnetically-levitated transportation system could increase considerably the demand for the metals that might be used in the necessary superconducting or magnetic alloys. Widespread use of nuclear power could alter sharply the consumption patterns of fossil fuels and the related pressures on transportation systems.

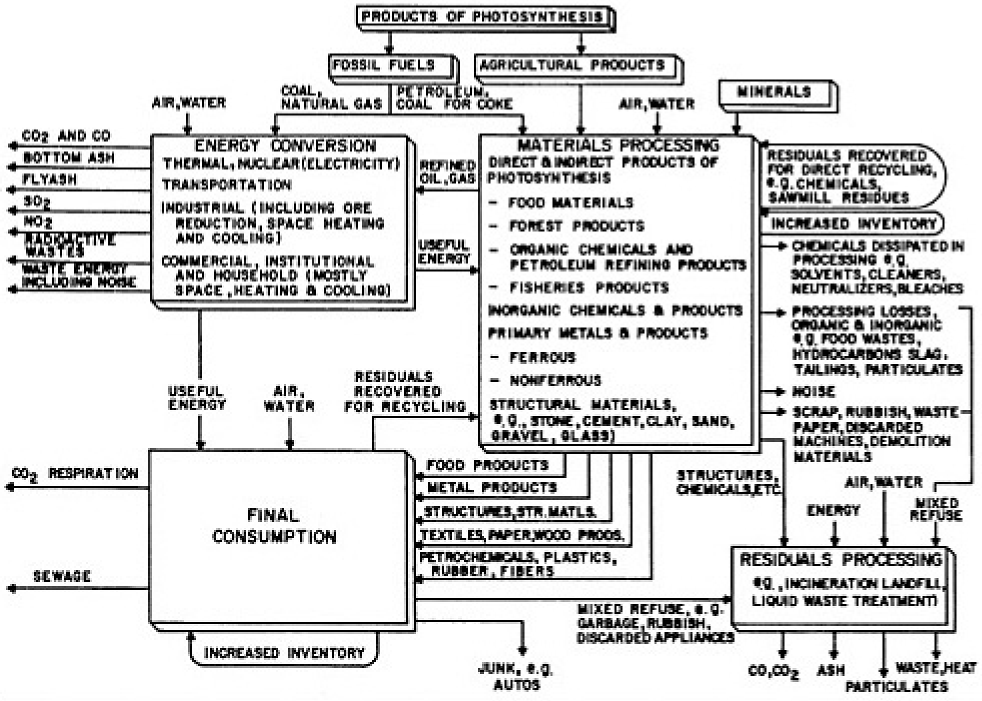
The materials cycle can be perturbed in addition by external factors such as legislation. The Clean Air Act of 1970, for example, created a strong new demand for platinum for use in automotive exhaust-cleanup catalysts. The demand may be temporary, since catalysis has been questioned as the best long-term solution to the problem, but whatever platinum is required will have to be imported, in large measure, in the face of a serious trade deficit. Environmental legislation also will require extensive recovery of sulfur from fuels and from smelter and stack gases; by the end of the century, the tonnage recovered annually could be twice the domestic demand. Such repercussions leave little doubt of the need to approach the materials cycle systematically and with caution. Some of the general characteristics of materials flows and interactions that would have to be taken into account in a model of the materials cycle are indicated in Figure 2.3 which was developed as a qualitative concept by Ayres and Kneese for dealing with the problem of residuals and recycling in relation to environmental quality.

It is readily apparent from an examination of Figure 2.3 that the currently limited knowledge concerning the materials flows operating on a world scale make it impractical to apply any comprehensive quantitative model except extremely crudely. However, on the scale of a single country, especially one such as the United States for which rather extensive statistical records of commodity flows are maintained, there is a greater likelihood that a satisfactory quantitative model for the overall materials cycle might be developed. The delineation of the critical information needed as inputs to provide a working quantitative description of the materials fluxes would be helpful not only for improving the model for highly industrialized countries, but also for indicating the minimum information needed from developing countries in order to develop more global models.

A quantitative model of the flux (rate of flow expressed in terms of mass per unit of time) of materials in the United States should be capable of giving valuable information for:

1. assessing the importance of materials in the national economy and their changes with time;
2. assessing the consequences of changes in the availability or demand for specific resources in the future;
3. examining the impact of changes in the materials flow in various sectors resulting from substitution of specific materials (whether for competitive, international, or environmental reasons) on the demand for materials in other sectors; and
4. estimating the changes in type and quantity of residuals that may result from changes in the materials used for given applications or from changes in the technology adopted for preparing and processing the materials.

FIGURE 2.3
FACTORS INVOLVED IN THE FLOW OF MATERIALS



INNOVATION IN THE MATERIALS FIELD

The Materials Revolution

Man historically has employed materials more or less readily available from nature. For centuries he has converted many of them, first by accident and then empirically, to papyrus, glasses, alloys, and other functional states. But in the few decades since about 1900, he has learned increasingly to create radically new materials. Progress in organic polymers for plastics and rubbers, in semiconductors for electronics devices, in strong, lightweight alloys for structural use has bred entire industries and accelerated the growth of others. Engineers and designers have grown steadily more confident that new materials somehow can be developed, or old ones modified, to meet unusual requirements. Such expectations in the main have been justified, but there are important exceptions. It is by no means certain, for example, that materials can be devised to withstand the intense heat and radiation that would be involved in a power plant based on the thermonuclear fusion, although the fusion reaction itself is not primarily a materials problem.

This expanding ability to create radically new materials stems largely from the explosive growth that has occurred during this century in our scientific understanding of matter. Advances in knowledge also have contributed much to the unifying ideas of materials science and engineering—wave mechanics, phase transitions, structure/property relationships, dislocation theory, and other concepts that apply to many classes of traditionally "different" materials. Certain semiconductor materials are perhaps the archetypal example of the conversion of fundamental knowledge to materials that meet exacting specifications. Our basic understanding of most materials, however, falls short of the level required to design for new uses and environments without considerable experimental effort. Hence, it is important to keep adding to the store of fundamental knowledge through research, although much empirical optimization will probably always be needed to deal with the complex substances of commerce.

An example of the latter is graphite which recently has solved important problems in missiles for rocket nozzles and as structural components in nuclear—power reactors. Yet, the necessary development was achieved by an enlightened empirical approach in a company which was very much material-source oriented. Graphite is a most complex material whose physical properties depend on the nature and processing of raw materials, on the quality of the initial carbon-containing material, on binder pyrolysis, and on a variety of processing variables. The most practical approach to development of a special graphite to withstand high temperature and pressure was a systematic study, therefore, of the dependence of properties on processing parameters. The starting point was an initial observation that hot pressing of normal-density carbon yields a body of high density and high strength. Science was able to provide only a very general framework for the planning and execution of this program. This case history also illustrates a governing feature of the traditional approach to materials development. Without a complete science framework and lacking even a few broad unifying concepts, the practitioner in graphite development necessarily needed to know a very large collection of facts based on past experience in graphite. For that reason, he was material-source oriented and tended to be more affiliated with the material-supplier than with the material-consumer.

In recent decades, however, the interest in materials properties has been broadening from that of the supplier to include that of the consumer. In some programs, such as aerospace and solid-state electronics, the material user has not been able to meet all his objectives with presently existing materials. This, in turn, has often caused the user to become involved in the discovery and development of completely new materials. It has also resulted in a closer working relationship between the material developer and the material user. Further, the programs which have run into materials limitations of the kind that determine success or failure tend, in general, to be those which are straining for the utmost out of sophisticated science and technology throughout the program.

The Systems Approach

Thorough systems analysis has been used to a moderate extent in materials science and engineering, but it must become basic to the field in view of the complexity of modern materials problems and of the fact that the materials cycle itself is a vast system. The need for the systems approach is apparent in the ramifications of replacing copper wire with aluminum in many communications used where the substitution would not have worked well until a few years ago. The move was triggered by changing relative prices and supply conditions of the metals. A research and development program produced aluminum alloys with the optimum combination of mechanical and electrical properties. The aluminum wire still had to be somewhat larger in diameter than copper wire, however. Thus, wire-drawing machines had to be redesigned, in part to avoid residual strain in the aluminum wire. Thicker wire, in addition, requires larger conduits, which take more space. And new joining techniques were necessary to avoid corrosion mechanisms peculiar to the aluminum wire.

Products like nuclear reactors, jet engines, and integrated circuits are systems of highly interdependent materials, each carefully adapted to its role in the total structure. The reaction of such a system to a breakdown at one point is evident in the intended use of a promising graphite-epoxy composite for the compressor blades of a British engine for an American jet airliner. The material was not developed on schedule, to the required degree of service reliability. The repercussions reached well beyond the resulting redesign of the engine. The respective governments were compelled to extricate both companies involved from financial crises, in an atmosphere of sharp debate over domestic and foreign policy.

Science-Intensive and Experience-Based Technologies

Science-intensive technology is used to designate those activities in which specific performance is at a premium and in which the generation of new fundamental understanding of materials is necessary before the desired performance can be achieved. Hence, the descriptor, science-intensive technology or sometimes high technology, usually denotes an emerging area where knowledge and practice are changing rapidly and where a widely based fund of experience and practical knowledge has not yet accumulated.

A familiar example illustrating high technology is the space program where it is mandatory that a component should function in the desired manner at the proper time. Because the entire success of an expensive mission may depend upon the proper functioning of this component, it is natural to expend whatever research and development is required to assure success. The actual cost of the materials making up the component becomes a secondary consideration. Another example is found in nuclear-power reactors. Fuel cladding must be of sufficient integrity to guarantee against hazardous release of radioactive by-products. In the design and fabrication of the fuel cladding, substantial effort at a sophisticated scientific and engineering level is justified to achieve reliability. In the solid-state electronics industry, we have an example in which highly sophisticated and costly effort on materials is warranted in terms of the overall product value; both the processing of semiconductor material and the assembly into discrete devices or integrated circuits require a degree of control which would be incredulous in most industrial situations.

Experienced-based technology, or low technology, refers to programs which are not science intensive—in other words, which rely on more empirical approaches or which may be relatively forgiving of manufacturing processing variations. Typically, large material quantities are involved so that unit material costs are important. Examples are the manufacturing of dishes and structural steels; many tires are assembled in traditional ways involving much hand work; long-standing approaches prevail in the construction of roads and highways where unit cost is of great importance; and the paper industry continues to use empirically-derived processes.

Pace of Innovation

There is a familiar pattern in the growth, development, and diffusion of a technology. At the birth and in the early stages of a technology, such as solid-state electronics or nuclear-power reactors, the pace of invention is high and the innovating company or nation may well achieve a commanding position in the market for its new technology. In this pre-marketing stage, cost is of secondary importance, or rather, is an administrative decision related to some perception of the eventual pay-off. Later, the inventive pace begins to slacken while, at the same time, other companies or nations with necessary educational level and technical competence are acquiring the knowledge and skills so that they may catch up. The formerly-commanding position of the original innovator is gradually eroded as the relevant technological capability diffuses nationally and internationally. In this stage, where the technology is termed as becoming mature, commercial advantage is kept by, or passes to, that company or nation which can most effectively minimize production and marketing costs while safeguarding the integrity of the product. Process innovation can then assume more importance than further product innovation.

The early stage of a technology, when the inventive pace is high, is often science-intensive. It seems that the high technologies in which the U.S. has been in the forefront, e.g. aerospace, computers, and nuclear reactors, have also been generally associated with international trade surpluses for the U.S. In the more mature stages, the science content of further developments in the technology is usually lessened, and the technology can be referred to as experience-intensive. Such technologies are more readily assimilated than high technologies by developing countries and are more likely to be associated with trade deficits for the U.S. inasmuch as the developing countries tend to enjoy lower costs, primarily through lower labor rates. When a technology reaches this phase, the U.S. runs the risk of becoming quite dependent for further developments in that technology on foreign enterprise. This may be acceptable for some technologies but not for others critical to national economic and military security. The primary metals industries are prime examples of such experience-based technologies facing severe foreign competition. Other industries in which technological leadership may have been lost by the U.S. are tires, and various consumer goods such as shoes and bicycles. Still other technologies, some of which are regarded as high technologies, are moving in the same direction, e.g., automobiles, consumer electronics, and certain aircraft products.

The implications for materials technology in the U.S. in order to meet foreign competition and maintain viable domestic industries are that high inventive pace must be created or maintained in certain fields so as to generate new high technologies and safeguard existing ones, and that the technological level must be raised and production costs lowered in selected, critical, mature industries. This must be done within the structure of U.S. industry which can be roughly classified, for our purposes, into the materials-producing and the materials-consuming industries. The former tend to be in the low-technology category, and the latter in the high-technology category. The high-technology industries, if their commercial bases are sufficiently large, are more accustomed to maintaining a balanced, but product-oriented, R and D effort than are the low-technology industries.

Disciplinary to Interdisciplinary

In the materials field, university departments have typically evolved along disciplinary lines—physics, chemistry, metallurgy, ceramics, polymers, with each discipline tending to specialize (as its name often indicates) in a particular class of materials or in a special approach to materials. Similar segmentation is apparent in the industrial sphere, with some industries specializing in metals, others in ceramics, in glass, in chemicals, or in crystalline materials for electronics. In addition, there has tended to be some separation in another direction, between materials science on the one hand, embracing the traditional scientific disciplines, and materials engineering on the other, embracing those parts of the engineering disciplines concerned with the processing and application of materials.

Such segregation is feasible only when the technical objectives, scientific or engineering, are relatively straightforward. For example, metallurgists may have all the requisite knowledge, both of the engineering requirements as well as the scientific and materials aspects, to cope with the problem of developing improved alloys for use as electrical conductors. In such a case, the customary, disciplinary approach can be quite adequate for pursuing a problem from the research phase to the production phase. But nowadays the trend in technology is towards ever more complex performance requirements, product and device designs, and dependence on more sophisticated knowledge of the physical phenomena that can be produced in an increasing diversity of materials. The areas of knowledge required to develop, say, an integrated circuit or a biomedical material are not at all coincident with the traditional disciplinary boundaries. It is obvious that many complex technologies call for knowledge and skills that cut across several disciplines, including science and engineering. Thus, we see an increasing need for interdisciplinary approaches in order to achieve technical objectives.

But the interdisciplinary approach is by no means limited to applied research and development programs. The same is happening in basic research in materials. The very core of materials science, the relation of properties to structure and composition, implies a need for the combined efforts of physicists, metallurgists, chemists, etc. In the past, the physicist has too often made unrealistic assumptions about the composition, purity, and quality of his research materials; the metallurgist has too often not understood sufficiently how the physical phenomena exhibited by a solid relate to its structure and composition.

Materials research provides a natural meeting-ground for professionals from the various scientific and engineering disciplines, from basic research to applied research, development and engineering. Clearly, the pressure for such interdisciplinary collaboration can only grow in the future.

MATERIALS IN A CHANGING CONTEXT

Materials and the associated science and engineering exist in a social and economic context that has changed markedly during the past decade. A pertinent indicator is the National Colloquy on Materials Science and Engineering held in April 1969: the proceedings[9] took virtually no notice of the field's close ties to the environment, an omission that could hardly occur today. Materials are involved also in other kinds of change: the energy crisis, the nation's problems with the balance of trade, federal efforts to stimulate and to assess technology; changing patterns in spending on basic and applied research and between civilian-oriented and defense- or space-oriented research and development; and the growing federal awareness of the importance of materials.

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[9] Materials Science and Engineering in the United States, Rustum Roy, Ed., Pennsylvania State University Press, University Park, Pa., 1970.

Two fundamental parameters in these matters are population growth and higher incomes. Between 1900 and 1970, the population of the U.S. rose 270%, to just under 205 million. For the year 2000 the Bureau of the Census projects a minimum population of 251 million and a maximum of 300 million. Percapita Gross National Product in constant 1958 dollars, meanwhile, has risen steadily, from $1351 in 1909 to $3572 in 1971. Both population and percapita GNP are expected to continue to grow, making ever more urgent the solution of materials-related problems.

Changing National Priorities

The materials system was shaped during World War II by diverse groups of commodity-oriented industries, educational disciplines, and technical societies, in response to the defense requirements for materials-limited hardware. This system was sharpened in the postwar era. It took the form of industrial faith in the profitability of materials research and development, an anticipated shortage of professionals in the materials field, and the materials needs of national programs for nuclear, aerospace, and defense hardware. During this period, commercial jet-powered air transportation, nuclear-power plants, space trips to the moon, and military operations in Korea and Viet Nam placed further emphasis on materials requirements.

Newly emerging national goals related to social needs, the state of the economy, and a de-emphasis of space, nuclear, and defense priorities led to a retrenchment in industrial research and development, a surplus of technical manpower in certain sectors, and the authorization of government-financed programs on housing, health and safety, energy, environmental control, transportation, recreation, and urban renewal.

Industries which were once commodity-oriented then diversified into market-oriented or integrated conglomerates; uncertainties arose as to whether or not materials science and engineering might be a technology or an educational discipline; governmental agencies became interested in technologies which were limited more by economics than by materials; and technical societies sought to re-group in response to the needs of interdisciplinary fields such as construction, pollution control, health and safety, etc. Since materials were available for hardware related to these requirements (except electronics), attention was focussed on the costs of housing, pollution control, health and safety, etc.—with emphasis on the processing of materials into the necessary hardware and its performance.

Operational research evaluating the costs of goods and services in comparison with their values as judged by the beneficiary led to reductions in industrial research in certain corporations concerned with steel, polymers, automobiles, electronics, exotic materials for aerospace, and also in free inquiry with expected but undefined rewards. The government began to focus on science and technology oriented toward national leadership in world economic competition and toward societal problems in education, energy, health, transportation, housing, and pollution abatement. The federal role stressed the need for additional mission-oriented industrial RD & E, and federal participation tended to be limited to projects of large national impact where the required resources were too large or too risky for corporate undertaking. This participation might take the form of direct support of joint ventures, or incentives resulting from changes in taxation and regulatory restraints.

Federal, state, and local support for education is also undergoing careful scrutiny under a new set of value-judgments and an apparent lack of professionals who are knowledgeable in emerging civilian technologies. The role of technical societies as communication media for professionals vis-a-vis their effectiveness in these societal technologies is likewise being reexamined.

Materials Resources

Society is concerned with the cost, performance, and functional value of the end-product, and is only incidentally conscious of the materials being used. Walter R.Hibbard, past director of the U.S. Bureau of Mines, has said that most Americans "have no appreciation of the scientific and engineering accomplishments that have enabled them to keep receiving these benefits over the years at relatively constant costs"[10].

Because of future prospects regarding decreasing supplies of traditional materials and the increasing promise of newer materials such as aluminum, plastics, semiconductors and nuclear fuels, it is more important than ever that people become familiar with the potential role of the science and engineering of materials. This evolving approach to materials, eventually affecting almost all of the goods and services with which we are familiar, will inevitably have a great influence on this nation's economic, aesthetic, and social well-being.

Striking changes are well under way in the balance between materials needs and world trade. Qualified sources report that the United States has "rapidly deteriorating, and by now very large," deficits in trade with minerals and raw materials, and with manufactured materials such as steel, textiles, and nonferrous metals[11]. But exports of finished products, which could help to offset these deficiencies, also are in a deteriorating position.

We are faced with the same question whether we are concerned with the depletion of the world-wide reserves or the deficiency of natural materials in the U.S. How can technology use our more available materials and less of scarce materials, to make improved products economically, and in quantities to keep pace with growing demand?

By 1980, our national need of materials is expected to be 40% greater than it is today, and today we require a greater supply of materials than at any previous time in our history. The U.S. already depends on foreign

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[10] Walter R.Hibbard, "Materials Today and Tomorrow," Engineering for U.S. Benefit of Mankind, p. 33,

[11] Michael Boretsky, "Concerns About U.S. Present Trade Position in International Trade," Technology and International Trade, NAE, 1970, p. 36 (and p. 48).

supplies for most of its tungsten, chromium, manganese, platinum, mica, bauxite, cobalt, nickel, asbestos, and about a dozen other mineral commodities. Also, current engineering applications of zinc, nickel, copper, cobalt, lead, tin, and the precious metals are feared to be rapidly depleting these resources.

William J.Harris, Jr., a past executive director of the Materials Advisory Board, calls attention to the countervailing trend, however, that during the last three decades "there have been more significant advances in a wider range of materials than in any comparable period in the history of the world."[12]

As an instance of how new technology has generally enabled industry to keep pace with growing demand, Hibbard[13] gives the example that "output from our mines has risen almost as steadily as the mineral values in the extracted ores have diminished." In particular, at the turn of the century, typical ore grades from copper mines were about 5% copper. The average grade of copper deposits mined today in the U.S. is less than 1% copper—about 14 pounds per ton. And new technology may make it practical to mine down to 4 pounds per ton. Although our copper grades have decreased, technology still allows us to produce copper at a reasonable price.

While improved extraction technology may ease our dependence on foreign sources of raw materials, improved technology in the other stages of the materials cycle will also greatly enhance our materials utilization. Figure 2.4 illustrates some of the social and technical pressures important at various stages of the economic utilization of materials. Clearly, a strong materials technology is required for industry to be responsive to these pressures in the production of goods at reasonable costs.

Besides the direct application of materials science and engineering to technology, innovation in the field can have important consequences for materials demand and consumption patterns, the consumption of energy, and the quality of the environment. Materials science and engineering can play a vital role in meeting man's needs for better transportation equipment, prosthetic devices, and new energy generation, transmission and storage methods. By wreaking these technological changes, it can often change drastically the consumption patterns for materials and energy. New materials made from more abundant raw materials can often be developed as substitutes for old ones made from scarcer or ecologically less desirable raw materials; new ways can often be found for performing needed technological functions, e.g. transistors have replaced vacuum-tube triodes as basic amplifying elements in electronic circuits,and integrated circuits have replaced boxes of complex electronic equipment assembled from discrete components. Looking ahead with another example, present work in certain forms of levitated ground transport, if successful, could lead to greatly increased demands for new magnetic or superconducting alloys. Or again, development of suitable catalysts based on relatively abundant materials could significantly reduce the demand for platinum catalysts in treating automobile exhaust gases.

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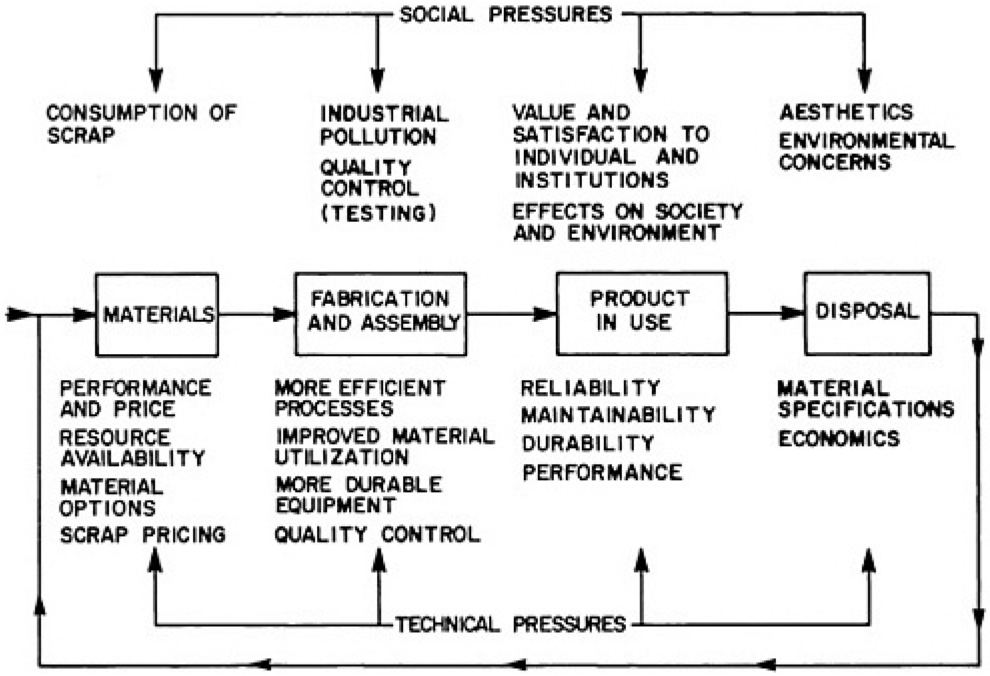
[12] SAMPE Quarterly, April 1971, p. 22.

[13] Walter R.Hibbard, "Materials Today and Tomorrow." Engineering for U.S. Benefit of Mankind.

FIGURE 2.4
MATERIALS UTILIZATION SHOWS SOCIAL AND TECHNICAL PRESSURES ON THE MATERIALS SCIENTIST AND ENGINEER



Energy, Environment

Materials, energy, and the environment are closely interrelated. The emergence of energy as a national problem of the first rank was reflected in mid-1973 in the President's establishment of a White House Energy Policy Office and his call for drastically increased federal spending on energy R & D. At the same time the President asked Congress to authorize a Cabinet-level Department of Energy and Natural Resources and the splitting of the Atomic Energy Commission into an Energy Research and Development Administration and a Nuclear Energy Commission. The energy problem also is reflected in the formation of the Electric Power Research Institute (EPRI) by public and private utilities that account for about 80% of the nation's generating capacity. This Institute will supervise research and development for the electric utility industry and plans to spend some $100 million in 1974, its first year of full operation. EPRI will be funded by self-assessment of member companies and will also seek to work with the federal government and equipment manufacturers.

Materials science and engineering has much to contribute in virtually all phases of the energy field; making new forms of generation possible, e.g. by finding solutions to the problem of material swelling under radiation damage in nuclear reactors; enabling new systems of electrical power distribution, e.g. through superconducting or cryogenic transmission lines; finding more efficient ways to store energy, e.g. through solid-electrolytic batteries or fuel cells; and developing more effective ways of using and conserving energy, e.g. through optimized materials processing and manufacturing operations.

National concern for the environment has been recognized in the past few years by extensive federal legislation as well as by the creation of the Environmental Protection Agency and the Council on Environmental Quality. Environmental matters also achieved international status with the Stockholm Conference on the Human Environment, held in mid-1972 under the aegis of the United Nations General Assembly. This concern was formalized in December 1972 when the General Assembly established a new unit, the U.N. Environmental Programme.

In the field of environmental quality, materials science and engineering has much to offer in the development of cleaner materials processes, effective uses for waste materials, materials and designs more adaptable to recycling, and in instrumentation to monitor and control pollution.

The U.S. Trade Balance

Materials are important factors in this country's balance of trade. The National Commission on Materials Policy has stated that, in 1972, the U.S. imported $14 billion worth of minerals (including petroleum) and exported $8 billion worth, for a net deficit of $6 billion. If the trends of the past 20 years persist according to the Commission, the deficit could top $100 billion annually by the year 2000. In 1970, the U.S. imported all of its primary supplies of chromite, columbium, mica, rutile, tantalum, and tin; more than 90% of its aluminum, antimony, cobalt, manganese, and platinum;

more than half of its asbestos, beryl, cadmium, fluorspar, nickel, and zinc; and more than a third of its iron ore, lead, and mercury. Certain science-intensive materials, on the other hand, including organic chemicals and plastics and resins, have produced, consistently, a positive balance of trade (Table 2.5).

The country's balance of trade has suffered from growing imports of manufactured products. This has happened particularly with low-technology (experience-intensive) goods and, to a lesser extent, with high-technology (science-intensive) goods (even allowing for a degree of controversy over which is which). It appears, in fact, that the U.S. has lost its technological leadership in some product areas, although cause-and-effect relationships among research and development budgets, technological initiative, and foreign trade are difficult to establish clearly (and lie, in any case, beyond the purpose of COSMAT).

The federal government has initiated modest efforts to stimulate civilian research, development, and innovation, so as to help recover technological initiative (which may have been lost, for example, in steel and titanium). The goal is to make U.S. products more competitive at home and abroad, and much of the emphasis will be on manufacturing technology, including materials shaping, forming, assembly, and finishing. The federal efforts include the Experimental Technology Incentives Program of the National Bureau of Standards in the Department of Commerce and the Experimental R&D Incentives Program of the National Science Foundation.

Technology Assessment

Technology assessment has long been practiced, in varying degree, in both industry and government, but a formal federal apparatus was established only recently, by the Technology Assessment Act of 1972. The Office of Technology Assessment and other mechanisms created by the Act are designed to give the Congress a stronger in-house grasp of the relative merits and side effects of alternative technologies. The Act did not establish a formal technology assessment function in the Executive Branch. The birth of the Office of Technology Assessment appears nevertheless to be stimulating similar efforts in parts of the Executive Branch.

The increasing diversity and complexity of technological products and the materials, often unfamiliar, from which they are made have posed increasingly severe burdens on the average consumer. As a result, consumers have become more concerned with the reliability, durability, safety, flammability, and toxicity of products. These pressures, in turn, translate into new challenges to materials science and engineering, introducing additional performance specifications alongside the more traditional ones.

The Federal Approach to Materials

The federal government has not yet developed a comprehensive national policy on materials. Materials-related responsibilities are diffused among a variety of formal and ad hoc committees and advisory groups, such as the

TABLE 2.5 U.S. Trade Balances in Illustrative Product Categories

	1960	1965	1970
Aircraft and Parts	$1187	$1226	$2771
Electronic Computers and Parts	44	219	1044
Organic Chemicals	228	509	715
Plastic Materials and Resins	304	384	530
Scientific Instruments and Parts	109	245	407
Air Conditioning and Refrigeration Equipment	135	207	374
Medical and Pharmaceutical Products	191	198	333
Rubber Manufacture	108	119	–28
Textile Machinery	104	54	–37
Copper Metal	–62	–132	–171
Phonographs and Sound Reproduction	15	–36	–301
Paper and Paper Products	–501	–481	–464
Footwear	–138	–151	–619
TV’s and Radios	–66	–163	–717
Iron and Steel	163	–605	–762
Petroleum Products	–120	–464	–852
Textiles and Apparel	–392	–757	–1542
Automotive Products	642	972	–2039

Source: U.S. Department of Commerce

Interagency Council for Materials. The Government is assisted also by groups like the National Materials Advisory Board and the Committee on Solid State Sciences in the National Research Council. The gradual emergence of a more coherent federal approach to materials questions, however, would appear to be implicit in certain developments of the past few years.

The Resource Recovery Act of 1970 created a National Commission on Materials Policy, whose charge was "to enhance environmental quality and conserve materials by developing a national materials policy to utilize present resources and technology more efficiently, to anticipate the future materials requirements of the nation and the world, and to make recommendations on the supply, use, recovery, and disposal of materials." The Commission reported to the President and to the Congress in June 1973.

The Mining and Minerals Policy Act of 1970 requires the Department of the Interior to make annual reports and recommendations for action in relation to a national minerals policy. The Second Annual Report under this Act was published in June 1973.

The creation of a Materials Research Division in the National Science Foundation brought into clearer focus the existence of a multidisciplinary materials-research community.

Recent years have also seen considerable interest in the idea that the earth's finite content of resources for industrial materials (including fuels) restricts severely the industrial growth that traditionally has been considered the basis of economic and societal health[14]. This concept of "limits to growth," and the related idea of a "steady-state society," are not within the scope of this study. They are, however, further indications of the changing context in which materials science and engineering exists and in which, we believe, the field has vital contributions to make.

NATIONAL AND INSTITUTIONAL CAPABILITY

Materials activities are clearly sizable in this country, where 6 percent of the world's population accounts for somewhere between a quarter and a half of the world's annual consumption of natural resources. The U.S. is very strong in materials science and engineering, but certain weaknesses, if unattended to, could progressively erode the nation's capability to meet the materials needs of its people. These weaknesses are due in part to the diffusion of responsibility for materials plans and programs at the federal level. To a considerable degree, the same diffusion of responsibility is found in the universities, in both education and research. Contributing also to weaknesses in materials are shortcomings in the generation and application of basic knowledge.

National capability in materials science and engineering relies on the trained manpower and basic knowledge produced by the universities and on the application of basic knowledge by industry and other mission-oriented institutions. An organization is better able to assess and exploit new knowledge

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[14] See, for example, "Materials in a Steady State World," H.Brooks, Metallurgical Transactions 3 759 (1972).

generated elsewhere when it is able itself to generate new knowledge. Thus, knowledge moves more readily from the universities to industry when companies do an appropriate amount of well-chosen basic research. It moves more efficiently also when universities conduct an appropriate amount of applied research. Current difficulties on both scores are pointed out later in this chapter under Universities and Industrial Research and Development.

The importance of materials suggests that materials science and engineering should be a prolific producer of knowledge. That this is so is indicated by the literature as abstracted in Chemical Abstracts. In 1970, 276,674 papers and patents were abstracted, of which 45 percent were in materials science and engineering. Over the past two decades, the world-wide literature in materials science and engineering has maintained an annual growth rate of 9 percent, whereas the annual growth rate for Chemical Abstracts as a whole has dropped from 8.8 percent in 1950–60 to 6.7 percent in 1960–70. Materials literature originating in the U.S. has been growing in recent years at 11 percent annually as compared with 13 percent for the U.S.S.R. The latter country overtook the U.S. in materials publications as far back as 1957. The U.S. produced about 25 percent of the materials papers in 1970; the U.S.S.R. 33 percent; and Japan 5.8 percent. In the U.S., educational institutions were the chief source (50%) of the materials literature, followed by industry (25%),and government (15%). The U.S. Accounted for 40 percent of the patents in 1970, and Japan 12.9 percent.

Manpower

Existing data on scientific and engineering manpower generally are not categorized along the multidisciplinary lines of materials science and engineering. We have used a list of specialties characterizing the field, therefore, to extract manpower data from prime sources. On this basis, it appears that materials science and engineering involves some 500,000 of the 1.8 million scientists and engineers in the U.S. We estimate (Table 2.6) that there is a full-time equivalent of 315,000 scientists and engineers in the field, including about 115,000 full-time practitioners. Within the latter group are approximately 50,000 professionals holding materials-designated degrees. Engineers, even without counting the materials-designated professionals, constitute the largest manpower group in materials science and engineering; they number 400,000 individuals, and correspond to a full-time equivalent of some 200,000. The situation with respect to women and minority groups in the materials field appears to be no different from that in science and engineering generally.

The current state of manpower data for materials science and engineering, and our knowledge of the relevant patterns of manpower flow, are such that nothing exceptional can be said of the field in comparison with the traditional disciplines, provided that external factors remain essentially unchanged. However, as the role of materials science and engineering in meeting societal needs becomes more widely understood, particularly in connection with energy and environmental problems, it is quite likely that there will be an increasing demand for scientists and engineers in the materials field.

TABLE 2.6 Estimates of Manpower in Principal Disciplinary Sectors of Materials Science and Engineering

		Full-Time Equivalent	
Discipline	Total Manpower	MSE Manpower	
		Total	Doctorates
Chemists	150,000	50,000 (16%)	19,000 (51%)
Physicists	45,000	15,000 (5%)	8,000 (22%)
Metallurgists	40,000	40,000 (13%)	5,000 (13%)
Ceramists	10,000	10,000 (3%)	1,000 (3%)
Other Engineers	1,200,000	200,000[b] (63%)	4,000 (11%)
	1,445,000[a]	315,000 (100%)	37,000 (100%)

Note: A detailed profile of scientists and engineers in the field of materials is presented in Appendix 2A of this chapter (pp. 2–58 to 2–93).

[a] The total number of scientists and engineers in the U.S. is about 1.8 million

[b] Approximately 400,000 engineers are involved significantly in materials science and engineering. We estimate, conservatively, that they divide their efforts equally between materials and other engineering activities and thus are equivalent to 200,000 engineers working full time in materials.

It should be emphasized that the boundaries of materials science and engineering are blurred and continually evolving. The central disciplines and subdisciplines include solid-state physics and chemistry, polymer physics and chemistry, metallurgy, ceramics, and portions of many engineering disciplines. In a broad sense, the field also includes segments of mechanics; of organic, physical, analytical, and inorganic chemistry; and of chemical, mechanical, electrical, electronic, civil, environmental, aeronautical, nuclear, and industrial engineering (Table 2.7).

Trends in Basic and Applied Research

The relative economic austerity of the past few years has been felt in basic and applied research in both industry and government. Nonfederal spending on research and development has virtually leveled off (in constant dollars), while federal spending has been declining (Figure 2.5). In current dollars, total federal spending on research and development has been rising slowly since 1970, but the emphasis has been shifting away from defense and space toward civilian-oriented areas (Figure 2.6). Expenditures on space have been falling, while spending on domestic programs has been rising slightly faster than on defense research and development (although starting from a much smaller base). In constant dollars, federal spending on both basic and applied research leveled off in the late 1960's; more recently, spending on basic research has declined slightly, while that on applied research has risen slightly (Figure 2.7).

Government Support of Materials Science and Engineering

Materials science and engineering has been shaped in a major way during the past two decades by federal research and development programs that evolved in response to national needs and goals. Direct federal funding of materials R&D (which amounted to 1.7 percent of the total federal R&D budget) totaled some $260 million* in fiscal 1971, according to the Interagency Council for Materials; in constant dollars this figure is about equivalent to the $185 million spent in fiscal 1962 (Figure 2.8). (Indirect federal funding of materials R&D through hardware contracts is conservatively estimated to equal direct funding, giving a total of some $0.5 billion in federal materials R&D in 1971. A breakdown of how the federal funding of materials R&D has changed from 1967 to 1971 is given in Tables 2.8 to 2.12.

More detailed data on how the federal support of materials R&D by Agency, Type of Research, and Performer are given in Table 2.13, and by Agency and Class of Materials in Table 2.14. Only one agency, the National Science Foundation, has an identified mandate to support science and technology

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* Other data suggest that the figure may be as high as $300 million, depending on the definition of terms. Some agencies, and COSMAT, consider research in solid-state physics, for example, to be materials research, while others do not.

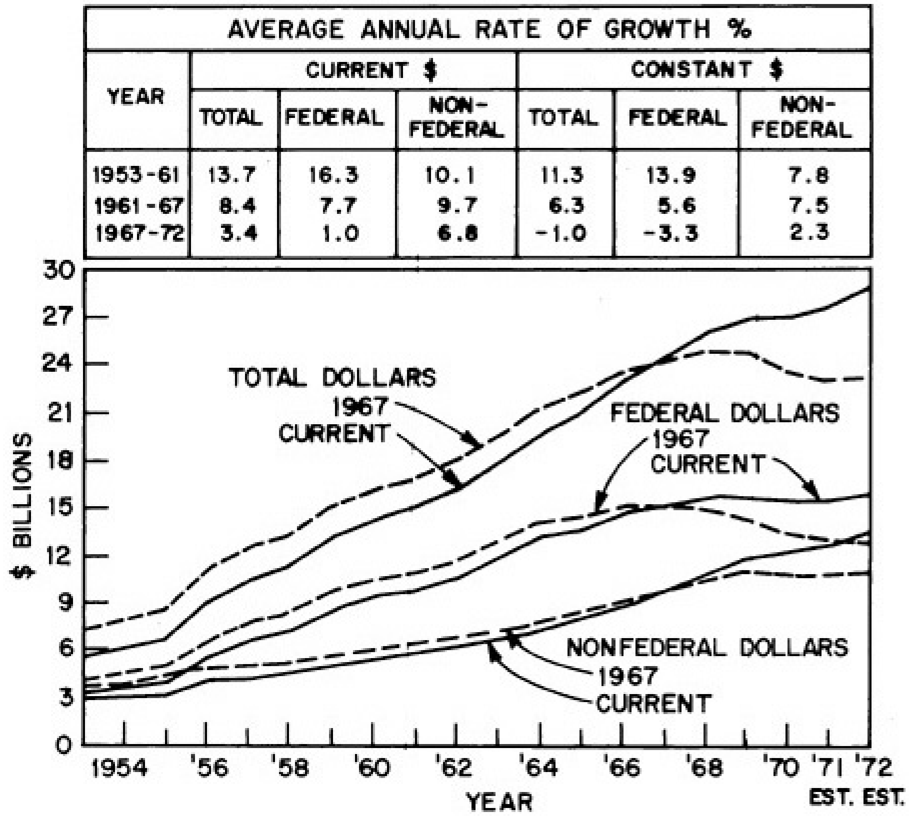
TABLE 2.7 Distribution of Materials Scientists and Engineers by Category of Activity

Category	% of Professionals in Category Who Are in MSE	% of Total MSE[a]	
FROM THE SCIENCE REGISTER			
Polymer and Organic Chemistry	51	6.7	
Physical Chemistry	76	3.4	
Analytical Chemistry	60	2.6	
Solid-State Physics	93	2.0	
Inorganic Chemistry	85	1.8	
Other Physics	17	1.6	
Other Chemistry	15	1.5	
Atomic and Molecular Physics	96	0.7	
Optics	38	0.5	
Earth Sciences	2	0.2	
			21%
FROM THE ENGINEERS REGISTER			
Structural Engineering	42	12.6	
Metallurgical Engineering	100	11.0	
Electromagnetic Engineering	42	10.2	
Chemical Engineering	92	9.5	
Work Management and Evaluation	18	8.8	
Dynamics and Mechanics	40	7.7	
Engineering Processes	60	5.4	
Heat, Light, and Applied Physics	75	5.4	
Automation & Control Instrumentation	45	4.7	
Ceramic Engineering	100	1.9	
Information and Mathematics	20	1.8	
Other Engineering	30	0.1	
			79%
			100%

[a] The distributions between the science and engineering portions of this listing have been adjusted to 21% and 79% respectively, in accordance with the physics plus chemistry percentages shown in Table 2.6.

Source: 1968 National Register of Scientific and Technical Personnel (National Science Foundation) and 1969 National Engineers Register (Engineering Manpower Commission) .

FIGURE 2.5
RESEARCH AND DEVELOPMENT SPENDING IN THE UNITED STATES 1953–72

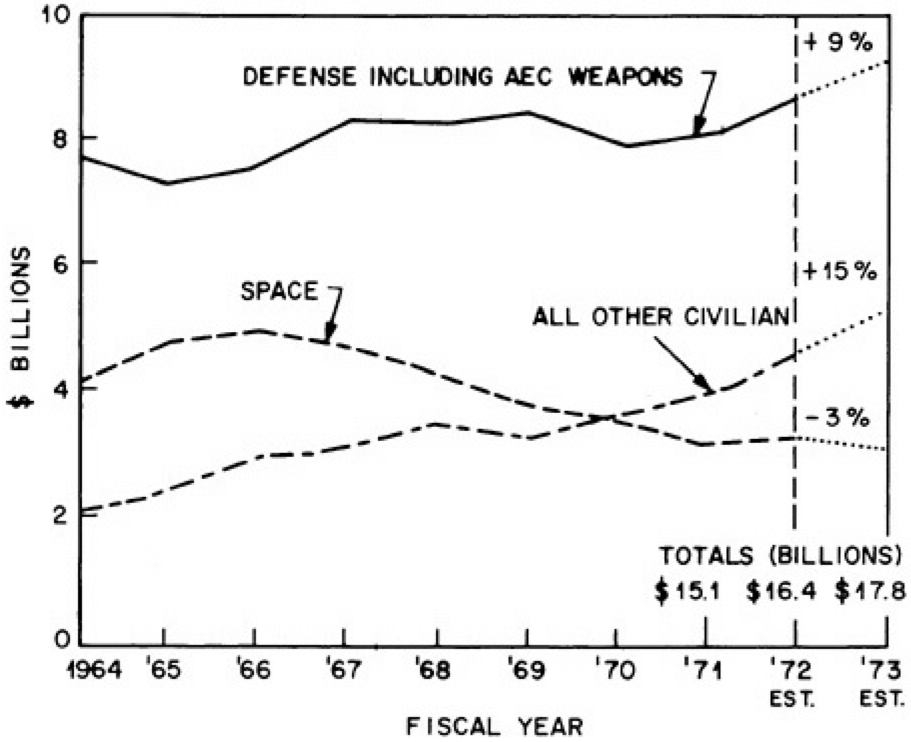


AVERAGE ANNUAL RATE OF GROWTH %

YEAR	CURRENT $			CONSTANT $		
	TOTAL	FEDERAL	NON-FEDERAL	TOTAL	FEDERAL	NON-FEDERAL
1953-61	13.7	16.3	10.1	11.3	13.9	7.8
1961-67	8.4	7.7	9.7	6.3	5.6	7.5
1967-72	3.4	1.0	6.8	-1.0	-3.3	2.3

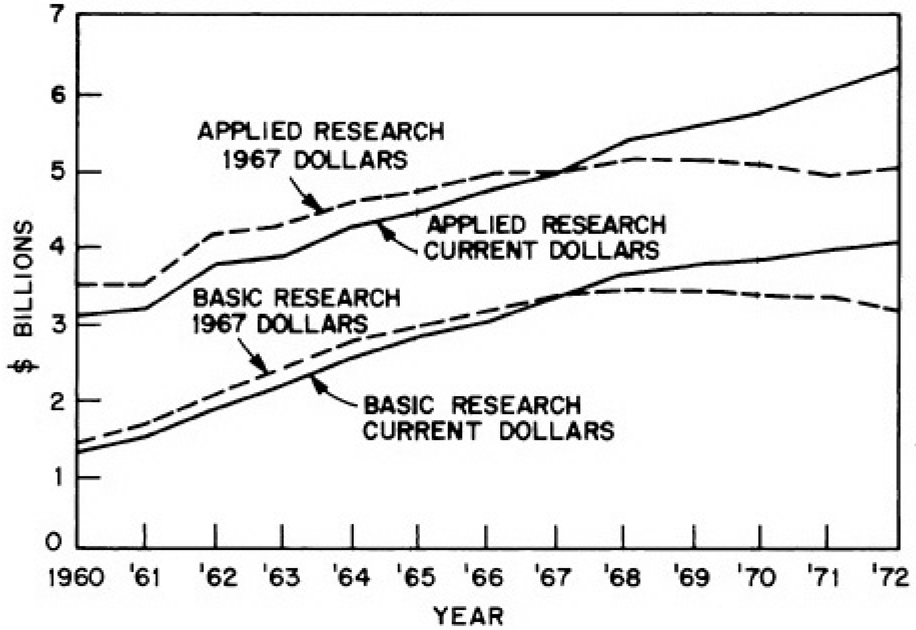
SOURCE: NATIONAL SCIENCE FOUNDATION (1972)

FIGURE 2.6
CONDUCT OF FEDERAL RESEARCH AND DEVELOPMENT (OBLIGATIONS CURRENT DOLLARS)



SOURCE: OFFICE OF SCIENCE AND TECHNOLOGY (1972)

FIGURE 2.7
TRENDS IN FEDERAL BASIC AND APPLIED RESEARCH



SOURCE: NATIONAL SCIENCE FOUNDATION (1972)

FIGURE 2.8
DIRECT GOVERNMENT FUNDING FOR MATERIALS RESEARCH 8 DEVELOPMENT

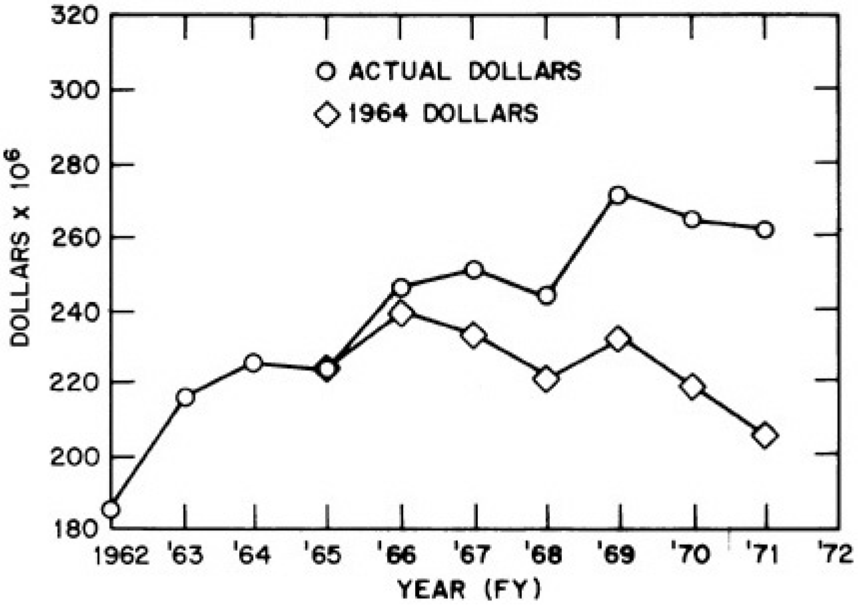


TABLE 2.8 Distribution of Federal Materials R&D Effort by Class of Materials

	Percentage Effort	
Material	1967	1971
Metallic	39.3	37.5
Inorganic nonmetallic	23.6	23.8
Organic	20.3	20.6
Composite	8.5	9.9
Fuels, lubricants, fluids	2.4	2.0
Other	5.9	6.1
	100.	100.
	($248.05M)	($260.2M)

TABLE 2.9 Distribution of Federal Materials R&D Effort by Research Activity

	Percentage Effort	
Activity	1967	1971
Basic Research	41.0	37.5 ($ 97.6M)
Applied Research	54.7	53.8 ($140.0M)
Experimental Development	4.3	8.7 ($ 22.6M)
	100.	100. ($260.2M)

TABLE 2.10 Distribution of Federal Materials R&D Effort by Performing Organization

	Percentage Effort	
Performing Organization	1967	1971
University	22.1	20.0 ($ 52.15M)
Industry	19.8	19.2 ($ 49.85M)
Government In-House	31.0	35.5 ($ 92.4M)
Federal Contract Research Centers	24.1	22.6 ($ 58.7M)
Other Non-Profit	3.0	2.7 ($ 7.1M)
	100.	100. ($260.2M)

The data in Tables 2.8 to 2.11 are derived from the following two sources:
a CCMRD Survey of Federal Directly Supported Materials R&D, May 1964 (for FY 1962 through FY 1964)
b ICM Survey of Federal Directly Supported Materials R&D, August 1971 (for FY 1965 through FY 1971)

TABLE 2.11 Distribution of Federal Materials R&D Effort by Supporting Agency

	Percentage Effort					
Supporting Agency		1965		1967		1971
AEC		34.4		34.4		31.6
DOD:		38.6		36.9		38.5
ARPA	5.6		9.0		7.7	
Air Force	16.5		14.3		14.9	
Army	7.7		6.0		6.6	
Navy	8.8		7.6		9.3	
NASA		10.0		8.9		8.6
NSF		3.4		4.1		4.1[a]
Dept. Interior		1.9		1.6		1.3
NBS		3.1		3.1		4.0
Agriculture		5.9		7.3		8.7
DOT		2.1		1.4		1.7
HEW		0.5		2.1		1.4
HUD		–		–		–
		100.		100.		100.

[a] Does not include transfer of IDL's from ARPA.

TABLE 2.12 Distribution of Federal Materials R&D Effort by Agency and Material for FY 1967 and 1971

Supporting Agency	Metallic		Inorganic Non—Metals		Organic	
	1967	1971	1967	1971	1967	1971
AEC	47.6	39.4	51.7	55.1	1.2	8.8
DoD:	36.8	40.9	28.2	30.8	33.8	32.1
ARPA	8.9	8.3	15.5	15.0	4.2	4.1
Air Force	11.7	12.3	6.1	5.2	14.7	13.6
Army	6.1	7.5	3.4	3.2	9.5	7.2
Navy	10.1	12.8	3.2	7.4	5.4	7.2
NASA	8.9	12.8	9.0	2.7	10.3	7.7
NSF	1.7	2.1	–*	–*	0.7	1.0
Dept. Interior	3.1	2.2	0.9	0.5	1.0	1.8
NBS	1.3	1.9	3.3	4.0	2.7	3.4
Agriculture	–	–	–	–	35.7	42.4
DOT	–	0.2			–	0.3
HEW	0.5	0.6	1.3	0.2	4.0	2.5
HUD	–	–	–	–	–	–
	100.0	100.0	100.0	100.0	100.0	100.0
TOTAL FUNDING ($ thousands)	97,450	97,550	58,600	61,900	?50,400	53,650

* NSF support for inorganic nonmetallic materials is contained in “solid state.”

Supporting Agency	Composite		Fuels, etc.		Other	
	1967	1971	1967	1971	1967	1971
AEC	4.8	13.1	–	–	11.8	10.0
DoD:	80.7	70.8	66.4	71.7	–	–
ARPA	11.9	1.7	–	–	–	–
Air Force	56.2	54.8	16.0	8.5	2.7[a]	1.9[a]
Army	1.4	5.8	31.9	45.3	–	–
Navy	11.2	8.5	18.5	17.9	8.2[c]	9.7[c]
NASA	5.2	10.0	33.6	28.3	–	–
NSF			–	–	55.6[a]	50.9[a]
Dept. Interior	–	–	–	–	–	
NBS	–	–	–	–	21.8[b]	27.4[b]
Agriculture	–	–	–	–	–	
DOT	–	–	–	–	–	
HEW	9.3	6.0	–	–	–	
HUD	–	–	–	–	–	
	100.	100.	100.	100.	100.0	100.0
TOTAL FUNDING ($ thousands)	21,000	25,900	5,950	5,300	14,650	15,900

[a] NSF and Air Force support for "materials, physics, solid state."

[b] NBS support for "analytical chemistry, physical chemistry, reactor radiation."

[c] Navy support for "energy conversion materials."

TABLE 2.13 Direct Federal Funding of Materials Research and Development by Agency, Type of Research, and Performer. (Fiscal Year 1971; millions)

	← Type →			← Performer →					
Agency	Basic Research	Applied Research	Experimental Development	University	Federal Contract Research Centers	Other Non-profit	Industry	Government InHouse	Total
Agriculture	$ 9.6	$ 11.8	$ 1.3	$ 0	$ 0	$ 0	$ 0	$22.6	$ 22.6
AEC	39.3	42.9	0	18.5	57.7	2.5	2.6	0.8	82.2
NBS	2.1	8.4	0	0	0	0	0	10.5	10.5
ARPA	14.0	6.0	0	10.7	0	0.7	6.6	1.9	20.0
Army	3.3	13.9	0	1.7	0	0.3	2.3	12.9	17.2
Navy	10.3	9.7	4.4	2.6	0	1.2	5.1	15.4	24.4
Air Force	3.9	23.4	11.5	2.5	0	0.3	26.6	9.4	38.8
HEW	1.4	2.2	0	1.4	0	1.2	0.9	0	3.6
HUD	0	0	0	0	0	0	0	0	0
Interior	0.1	3.4	0	0.3	0	0	1.8	1.3	3.5
NASA	4.7	14.7	3.2	0.8	0	0.8	3.9	17.3	22.6
NSF	8.9	1.7	0	10.7	0	0	N.A.	0	10.6
DOT	0	2.0	2.2	3.0	1.0	0	0	0.5	4.2
Totals[a]	$97.6	$140.0	$22.6	$52.2	$58.7	$ 7.1	$49.9	$92.4	$260.0
	← Total: $260M →			← Total: $260M →					

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[a] Totals may not add exactly because of rounding in the several compilations used for these figures.

Source: Interagency Council for Materials

Note: Other data suggest that the $260M total shown above may be as high as $300M and the University total as high as $75M, depending on definition of terms. Some agencies, and COSMAT, consider research in solid-state physics to be materials research, for example, while others do not.

TABLE 2.14 Direct Federal Funding of Materials Research and Development by Agency and Field of Materials. (Fiscal Year 1971; millions)

Agency	Metallic Materials	Organic Materials	Inorganic Nonmetallic Materials	Composite Materials	Fuels, Lubes, Fluids	Other Materials
Agriculture	$ 0	$22.8	$ 0	$ 0	$0	$ 0
AEC	38.4	4.7	34.1	3.4	0	1.6
NBS	1.8	1.9	2.5	0	0	4.3
ARPA	8.1	2.2	9.3	0.5	0	0
Army	7.3	3.9	2.0	1.5	2.4	0
Navy	12.5	3.9	4.6	2.2	0.9	0.3
Air Force	12.0	7.3	3.2	14.2	0.5	1.5[b]
HEW	0.6	1.6	0.1	1.5	0	0
HUD	0	0	0	0	0	0
Interior	2.2	1.0	0.3	0	0	0
NASA	12.6	4.2	1.7	2.6	1.5	0
NSF	2.1	0.6	a	a	0	8.1[c]
DOT	0.2	0.2	4.2	0	0	0
Totals[d]	$97.6	$53.6	$61.9	$25.9	$5.3	$15.9
Total: $260 M						

[a] Not reported under materials R&D

[b] Materials physics, solid state

[c] $7.6 solid state, 0.5 biomaterials

[d] Totals may not add exactly because of rounding in the several compilations used in these figures.

Source: Interagency Council for Materials

Note: Other data suggest that the $260 M total shown above may be as high as $300 M, depending on the definitions of terms. Some agencies, and COSMAT, consider research in solid-state physics to be materials research, for example, while others do not.

generally. All of the others, commanding 90 percent of the budget, support the science and technology related to their missions.

Governmental materials laboratories, which received about a third of the federal R&D funds in materials in 1971, concentrate primarily on identified, mission-oriented problems. To support this work, they do exploratory research at a level that appears to vary from laboratory to laboratory in the range of 5 to 15 percent of their total funding. Some federal laboratories have become centers of excellence in specific areas. These include the Air Force Materials Laboratory, Wright-Patterson Air Force Base, Dayton, Ohio, in composite materials; the Atomic Energy Commission's Oak Ridge National Laboratory in radiation damage and neutron diffraction; and the National Bureau of Standards in polymeric materials.

The government also operates the National Standard Reference Data System, which is administered and coordinated by the National Bureau of Standards. This program provides critically-evaluated numerical data on the physical and chemical properties of well-characterized substances and systems. The Bureau, in addition, operates the Standard Reference Materials program, which now can provide standard samples of more than 800 materials.

Universities

Some areas of materials science and engineering, such as metallurgy and ceramics, are full-fledged academic disciplines. Areas emerging as formal degree programs include materials science, polymer science, solid-state science, and materials engineering. Despite such programs, the nature and uses of materials are so broad and pervasive as to continue to require close interaction among many disciplines

At least half of the identifiable research on materials in universities is done on the 28 campuses where materials research centers have been established in the past decade. Twelve of these schools were selected in the early 1960's as the sites of Interdisciplinary Laboratories (IDL's). The IDL's were sponsored by the Advanced Research Projects Agency (ARPA) as an experiment in improving the sophistication of materials research and increasing the number of materials specialists. A notable feature of these university laboratories has been the availability of block funding for locally-selected research programs and central facilities. In July 1972, responsibility for the IDL program was assumed by the Materials Research Division of the National Science Foundation; the IDL's were then renamed Materials Research Laboratories. In the Spring of 1973 the Foundation announced plans for two new Materials Research Laboratories, one to focus on the technology of joining, the other on polymers.

The National Aeronautics and Space Administration (NASA) set up three block-funded programs at universities in the 1960's, but at lower levels of support than for the IDL's. In the same period, the Atomic Energy Commission (AEC) established block-funded materials research centers at three universities, one of them already an ARPA-IDL school. Since the start of these programs by ARPA, NASA, and AEC, 11 additional universities have formed analogous materials research centers, mainly on their own initiative. They use the concept of central facilities, but are mostly without block funding.

A COSMAT study found that, typically, these materials centers ranked high in education and individual basic research, the traditional functions of the university. Most of the centers ranked low in interaction with industry and in innovative methods of operation. Some centers have done a relatively significant amount of interdisciplinary work, one measure of which is the authorship of the resulting scientific papers. In three quarters of the centers, 10 to 15 percent of the papers covered by our evaluation were written jointly by faculty from two or more departments. This contrasts with an average of 2 percent for papers from materials-designated departments.

Because of the difficulty of obtaining comparable data from different schools, this evaluation does not pretend to be fully accurate and complete. It is true, nevertheless, that universities have produced relatively little so far in the way of new materials per se. An important reason, we believe, is that the academic community traditionally has resisted interdisciplinary and applied research. We have noted already that the reward structure within the university is tilted strongly toward the disciplines; likewise, no funding agencies have clearly rewarded excellence in interdisciplinary activities at universities. All of the materials research centers indicated that they plan to shift their emphasis somewhat toward applied research. The area mentioned most often was biomaterials. This field is highly interdisciplinary and intellectually stimulating, but the corresponding body of technology is much smaller than in other areas, such as ceramics, polymers, and electronic materials.

Materials Degrees: Formal undergraduate curricula in materials appear to be confined to materials-designated degree programs, which are located almost entirely in engineering schools. Some 60 programs of this kind are accredited in the country's 250 engineering schools. These and 30 unaccredited programs award annually somewhat more than 900 materials-designated baccalaureate degrees, or about 2 percent of the total engineering baccalaureates conferred annually. Currently, more than half of the materials-designated departments average fewer than 10 baccalaureates per year, a situation which will become increasingly difficult to justify.

About 50 institutions in the U.S. offer graduate degrees in materials. The 270 materials-designated doctorates awarded in 1971–72 amounted to about 7 percent of the total engineering doctorates conferred. In solid-state physics, which provides a major component of the professional manpower in materials science and engineering, doctorates awarded annually appear to number about 370. Annual output of materials-research doctorates awarded in chemistry and in nonmaterials-designated engineering programs is at least double the number in solid-state physics. Thus we estimate that the annual output of doctorates in the field of materials is about 1400, but there is much uncertainty in this figure because of difficulties in the "materials identification."

Research Funding: University research in materials is supported almost entirely by federal funds at an annual level (in 1971) of about $52.2

million* (Table 2.13). This was 20 percent of the $260 million** in total, direct federal support for materials research and development in 1971 and about 3 percent of total federal support for research and development in the universities. Some 35 percent of the support for university research in materials was provided by the Atomic Energy Commission and about 20 percent each by the National Science Foundation and the Advanced Research Projects Agency in the Department of Defense. (In fiscal 1973 the Foundation estimates its materials research support at $35 million, more than triple the $10.7 million of 1971, but the major part of the increase arises from internal regrouping into the “materials research” category.) Relatively little identified support is available as yet from agencies like the Departments of Health, Education and Welfare; Housing and Urban Development; and Transportation.

Almost 60 percent of the federal support for university research in materials goes to the 12 universities where the original NSF Materials Research Laboratories are located. About 15 percent of the support goes to the 16 additional schools that have materials research centers of other kinds, On the 12 campuses where the original NSF Materials Research Laboratories are located, slightly more than 25 percent of materials-research funds are received by materials-designated departments, slightly less than 15 percent by other engineering departments, and about 60 percent by physics and chemistry departments.

A useful source of information for analyzing federal support of university research on materials is the compilation of “Federal R&D Obligations to Universities and Colleges for Fiscal Year 1970” prepared by NSF. The distribution of the total obligation of the $1.395 billion for that year is shown in Table 2.15.

There is a disparity between the figure of $17.6 M for the identified materials topic of “metallurgy and materials” in Table 2.15 and the $52.2 M reported by ICM as the federal support to universities for materials R&D (Tables 2.10 and 2.12). The difference presumably arises from a more restricted definition of materials research in the NSF tabulation; it is likely that the latter corresponds to support to departments of “metallurgy and materials,”*** whereas the ICM data included materials support through physics, chemistry and other categories. Assuming this to be the prime source of the difference, it is useful to examine the ICM figure against that of the total for physical sciences and engineering in Table 2.15, i.e. those fields where almost all materials research will be conducted (although

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* The figure could be as high as $75 million, depending on definitions of terms. COSMAT and some agencies, for example, consider research in solid-state physics to be materials research, while others do not.

** The figure could be as high as $300 million, for the reason given in the preceding footnote.

***The fact that the proportion of funding (12.4% for “metallurgy and materials” in Table 2.15 to that for all engineering is close to the percentage of advanced degrees awarded in that field relative to all engineering supports this interpretation.

TABLE 2.15 Distribution by Field of Science of Federal R&D Support to Universities for FY 1970

Field	Amount (Dollars in Thousands)	Percent of Total
Physical Sciences:	283,114	20.28
Astronomy	32,111	2.3
Chemistry	70,205	5.03
Physics	176,629	12.65
Physical Science	4,169	0.30
Mathematics:	44,582	3.19
Environmental Sciences:	106,722	7.65
Engineering:	141,533	10.14
Aeronautical	16,217	1.16
Astronautical	18,002	1.29
Chemical	8,167	0.59
Civil	9,981	0.72
Electrical	31,963	2.29
Mechanical	11,904	0.85
Metallurgy and Materials	17,603	1.26
Engineering	27,696	1.98
Life Sciences:	565,094	40.48
Psychology:	62,298	4.46
Social Sciences:	47,144	3.43
Other Sciences:	144,748	10.37
	$1,395,923	100.

Courtesy Dr. Charles Falk, NSF

some may also be done under "environmental sciences" and the "life sciences"). The proportion of materials funding against that total of about $425 M is 13.9 percent. Bearing in mind that the NSF data appears to relate primarily to funds for "metallurgy and materials" departments, it is of interest to note the distribution of agency sources of funds for that category in Table 2.16 compared to that shown in Table 2.13 for total federally supported materials R&D.

Table 2.17 shows the proportions of federal agency funds for materials R&D in universities, as reflected by the NSF data (interpreted as applying mainly to materials departments). The differences between these figures and the agency totals in Table 2.18 provide the best current estimate of the federal funds for materials R&D universities going outside the materials departments. This tabulation indicates that federal support of university materials research allocated outside the materials department is more than twice as large as that for materials research within such departments (apart from the questionable data available for NASA and Department of Interior).

Industrial Research and Development

Accurate figures are not available for materials research and development in industry. Data for industrial R&D in general (Table 2.19) indicate that All Industries planned a 4 percent increase in spending in 1972 including federally-funded industrial R&D. The metals-producing industries—steel, monferrous metals, fabricated metals—were expected to remain essentially level in 1971–72 in current dollars. This would have meant an 8 to 10 percent decrease in research and development actually performed, because of rising costs. Decreases in work performed were also indicated in paper and in stone, clay, and glass. All Manufacturing showed an estimated increase of only 2 percent in 1972, again amounting to a decrease in R&D actually performed. Even in high technologies like aerospace (no change in 1972) and electrical machinery and communications (up 2 percent), R&D spending has not kept up with rising costs. Industrial research and development as a percent of sales (Table 2.20) held level or declined in 1972 in all areas except aerospace. Federally-funded research and development in All Manufacturing (Table 2.21) is declining, both in dollars and as a percentage of total industrial R&D.

More recent figures (Table 2.22) have shown a brightening picture for company-funded research and development, although substantial differences exist among individual industries. Spending on basic research in All Industries is projected to rise 25 percent in 1972–75, to $650 M; spending on research and development overall is expected to rise 22 percent in the same period, to just under $14 billion. The source of these figures, the National Science Foundation, notes the changing nature of industrial basic research. Companies generally are shifting toward "shorter-term, more relevant, and hence more economically-justifiable projects."

Industry in this country and abroad has produced many of the outstanding achievements of materials science and engineering. They include nylon; the transistor; the high-field superconductor; the laser; phosphors for television, radar, and fluorescent lamps; high-strength magnetic alloys; magnetic ferrites;

TABLE 2.16 Distribution of Federal Agency Support for "Metallurgy and Materials" R&D at Universities for FY 1970*

Agency	Support (Dollars in Thousands)	Percent
AEC	2,461	14.0
DoD	7,825	44.5
NASA	1,380	7.8
NSF	3,547[a]	20.2
Interior	1,992	11.3
NBS (Commerce)	–	–
Agriculture	240	1.4
DOT	–	–
HEW	158	0.9
HUD	–	–
	$17,603	100.

* Courtesy Dr. Charles Falk, NSF.

[a] The size of the NSF figure suggests that it is only for "engineering materials" in the NSF Engineering Division in FY 1970.

TABLE 2.17 Proportion of Federal Agency Materials R&D Funds Allocated to Universities—FY 1970*

Agency	Federal Materials R&D (Dollars in Thousands)		Allocated to Universities (Dollars in Thousands)		University Percent of Agency Total		Agency Percent of University Total	
AEC		86,300		19,400		22.5		32.9
DoD:		92,350		18,800		20.3		31.9
ARPA	20,000		12,750		63.8		21.6	
Air Force	34,150		2,000		5.9		3.4	
Army	16,400		1,450		8.8		2 5	
Navy	21,800		2,600		11.9		4.4	
NASA		25,800		800		3.1		1.4
NSF		10,150		10,150		100.0		17.2
Dept. Interior		3,850		350		9.1		0.6
NBS (Commerce)		9,900		0		0		0
Agriculture		22,700		2,100		9.3		3.6
DOT		4,200		3.650		86.9		6.2
HEW		7,800		3,800		48.7		6.4
HUD		100		0		0		0
		263,150		59,050		22.4		100.

* Derived from data in ICM Survey, August 1971.

TABLE 2.18 Comparison of Federal Materials R&D Support at Universities Between “Materials Departments” and “Other Departments” —FY1970

Agency	Total University Federal Materials R&D[a] (Dollars in thousands)	“Materials Departments”[b] (Dollars in thousands)	“Other Departments” (by difference)
AEC	19,400	2,461	16,939
DoD	18,800	7,825	10,975
NASA	800[c]	1,380	–580
NSF	10,150	3,547	6,603
Interior	350	1,992	–1,642
NBS (Commerce)	0	0	0
Agriculture	2,100	240	1,860
DOT	3,650	0	3,650
HEW	3,800	158	3,642
HUD	0	0	0
	59,050	17,603 (29.8% of total)	

[a] Data from ICM Survey, August 1971.

[b] Data from NSF Survey.

[c] Listed as “estimated” in the ICM Survey.

TABLE 2.19 Industrial Research and Development (Includes federally-funded industrial R&D)

	Expenditures				Change	
	1970	Est.	Planned			
	Actual	1971	1972	1975	1971–72	1972–75
	(Millions)				(Percent)	
Steel	$ 131	$ 122	$ 132	$ 149	8	13
Nonferrous Metals	134	165	155	234	–6	51
Machinery	1,727	1,831	1,923	2,173	5	13
Electrical Machinery and Communications	4,324	4,410	4,498	5,353	2	19
Aerospace	5,173	4,914	4,914	5,061	0	7
Autos, Trucks, and Parts, and Other Transportation Equipment	1,475	1,475	1,504	1,609	2	7
Fabricated Metals and Ordnance	183	176	183	210	4	15
Professional and Scientific Instruments	694	756	824	972	9	18
Lumber and Furniture	24	31	36	38	16	6
Chemicals	1,809	1,827	1,882	2,145	3	14
Paper	119	133	133	166	0	25
Rubber Products	238	281	295	366	5	12
Stone, Clay, and Glass	188	169	169	198	0	17
Petroleum Products	608	492	522	606	6	16
Food and Beverages	198	208	225	263	8	17
Textile Mill Products and Apparel	64	60	66	81	10	23
Other Manufacturing	98	117	124	161	6	30
ALL MANUFACTURING	$17,187	$17,167	$17,585	$19,755	2	12
Nonmanufacturing	669	723	1,063	1,711	47	61
ALL INDUSTRIES	$17,856	$17,890	$18,648	$21,466	4	15

Source: National Science Foundation (1972).

TABLE 2.20 Industrial Research and Development as Percent of Sales*

	1970	1971	1972[a]	1975[a]
Steel	0.34%	0.31%	0.28%	0.26%
Nonferrous Metals	0.76	0.90	0.79	0.93
Electrical Machinery	8.51	8.17	7.72	7.23
Machinery, Other	3.08	3.08	2.96	2.61
Aerospace	19.02	20.05	20.88	17.92
Autos, Trucks, and Parts, and Other Transportation Equipment	2.73	2.23	2.05	1.71
Stone, Clay, and Glass	1.06	0.81	0.74	0.70
Fabricated Metals	0.44	0.41	0.40	0.37
Instruments	5.71	6.39	6.27	5.52
Chemicals	3.71	3.54	3.41	3.16
Paper	0.74	0.51	0.47	0.45
Rubber	1.36	1.49	1.43	1.34
Petroleum	2.29	1.76	1.73	1.66
Textiles	0.29	0.26	0.26	0.24
Food and Beverages	0.20	0.20	0.20	0.19
Other Manufacturing	0.13	0.14	0.14	0.13
ALL MANUFACTURING	2.63	2.47	2.32	2.08

* Sales figures are based on company data classified by major product line.

[a] 1972 estimated; 1975 planned.

Source: 1972 McGraw-Hill Survey of Industry Research and Development.

TABLE 2.21 Federally-Financed Industrial Research and Development (Amounts and percent of total R&D spending by industry)

	1971		1972[b]		1975[b]	
INDUSTRY	Percent	Million Dollars	Percent	Million Dollars	Percent	Million Dollars
Steel		[a]		[a]		[a]
Nonferrous Metals	5	$ 8	6	$ 9	6	$ 14
Machinery	12	220	10	192	8	174
Electrical Machinery and Communications	50	2,205	48	2,159	42	2,248
Aerospace	80	3,931	76	3,735	72	3,644
Autos, Trucks, and Parts, and Other Transportation	13	192	12	180	10	161
Fabricated Metals and Ordnance	3	5	3	5	3	6
Professional and Scientific Instruments	25	189	23	190	21	204
Lumber and Furniture		[a]		[a]		[a]
Chemicals	10	183	10	188	11	236
Paper	1	1	1	1	1	2
Rubber Products	15	42	14	41	12	40
Petroleum Products	5	25	5	26	5	30
Food and Beverages	1	2	1	2	1	3
Textile Mill Products and Apparel		[a]		[a]		[a]
Other Manufacturing		[a]		[a]		[a]
ALL MANUFACTURING	41	$ 7,008	38	$6,731	34	$6,770
Nonmanufacturing	68	492	65	691	60	1,027
ALL INDUSTRIES	42	$ 6,500	40	$7,422	36	$7,797

[a] Less than $500,000.
[b] 1972 estimated; 1975 planned.
Source: National Science Foundation (1972).

TABLE 2.22 Company-Funded Industrial Research and Development (Millions)

	Total R&D			Basic Research		
	1971	1972	1975 (Est.)	1971	1972	1975 (Est.)
All Industries	$10,643	$11,400	$13,950	$ 494	$ 520	$ 650
Drugs and Medicine	505	560	750	95	105	140
Industrial Chemicals	864	890	1,025	100	105	125
Petroleum	488	495	525	22	23	25
Electrical Equipment	2,230	2,400	3,000	109	115	145
Aircraft and Missiles	1,012	975	1,150	34	30	40
All Other	5,544	6,080	7,500	134	142	175

Source: National Science Foundation (1973).

and polyethylene. These developments occurred in industries that conducted long-range research to expand the basic knowledge on which the industry ultimately relied. By thus supplementing their experience-based approach to materials research and development, these industries established technological leadership for themselves and for their countries. The resulting cumulative national payoff, though difficult to measure, is substantial.

Our current shift from aerospace, atomic energy, and defense toward more civilian-oriented technologies offers industry a wide variety of fresh technical challenges: in the environment, in energy, in the quality and safety of consumer goods. Many such challenges will be met only with the help of sustained basic and applied research. Yet, industry has been cutting back its relatively basic programs in the past few years. The science-intensive industries have retrenched significantly; the experience-based industries in many cases have virtually eliminated their basic research.

Competitive pressures and the cost of research and development are rising steadily. A not-uncommon view is that the penalties of failure in R&D and the liability of high engineering risk have grown too great, while the rewards of success and the achievement of advanced product-performance are too easily appropriated by others. Some companies now are reluctant to undertake programs that do not promise to begin to pay for themselves in five to ten years at the most. The payoff period for basic research in materials, in contrast, although it tends to be shorter than in other areas, may sometimes exceed 10 years. A company that is not a technological leader may find that new technology is obtained most sensibly from other companies, by cross-licensing or by royalty agreements. But the company striving to achieve or maintain technical leadership will find a balanced research and development program essential to its success.

More broadly, were basic research in materials science and engineering to be eliminated, the rate of introduction of new technology might not slow noticeably for several years. But then the nation’s capability would decline-precipitously in some high-technology areas, more slowly in low-technology areas. The country could sink to a seriously inferior position internationally in ten to twenty years. Many industrial managements and, perhaps, the general public are not prepared to wait that long for the fruits of research. But industry should recognize more widely, we believe, that research in materials characteristically has returned good value and that the payoff is more assured than in many other fields. Progress in materials may not depend on public support to the same extent as does astronomy, let us say, but for government, as for industry, materials science and engineering represents a sound investment. As in other fields, the decisions to be made often relate to the appropriate roles of government and private initiative in undertaking research. These can be hard decisions, but they must be made.

OPPORTUNITIES FOR MATERIALS SCIENCE AND ENGINEERING

In this chapter, we have noted that the shifting of national priorities for technology in no way lessens, and generally increases, the demands on materials science and engineering. These demands are sharply revealed by concerns over possible shortages of critical materials and of energy, and over the harmful effects on the environment by man's operations with materials. Merely to sustain our standard of living, let alone advance it, has dramatic impact on international trade, and so adds further dimensions to the challenge. Moreover, there is in the background society's ambivalent view of technology—a love-hate relationship—never quite knowing whether to embrace it or to reject it. As a result, the challenges to materials science and engineering are exquisitely complex. But just as in the past when properly manned and supported, materials science and engineering has met the demands of national defense, space, and other high technologies, so can it address successfully the problems of the newer societal concerns.

A specially important opportunity for materials science and engineering in the present context is conservation. The materials community is now challenged to find positive ways to conserve natural resources and energy, to conserve the environment, to conserve man's standard of living and the quality of life. The latter relates particularly to interactions between people and nations with different backgrounds and cultures.

APPENDIX 2A PROFILE OF MANPOWER IN MATERIALS SCIENCE AND ENGINEERING

Method of Analysis

The National Science Foundation has maintained an activity directed to the collection and statistical analysis of data concerning scientists and engineers in the U.S. for many years. The files of the NSF are a principal source of statistical information about technical manpower. With the generous cooperation of the NSF and the National Research Council, COSMAT was able to analyze the 1968 National Register of Scientific and Technical Personnel and the 1969 National Engineers Register.

The National Register of Scientific and Technical Personnel (frequently referred to hereafter as the Science Register) is a body of data on scientists in the U.S. that is maintained by NSF through contacts with a group of scientific societies. Data were obtained by periodically (biannually) sending questionnaires to all scientists who could be identified by the societies involved.

The National Engineers Register is a file of data on engineers in the U.S. that is accumulated by the Engineers Joint Council and NSF through questionnaires sent to a sample of engineers who are members of societies associated with the Engineers Joint Council. It is the principal data-base available concerning the engineering profession in the U.S.

An early problem faced by COSMAT in attempting to study materials scientists and engineers was that of identifying the population involved. That is, it was necessary to answer the question, “Whom shall we call a materials scientist or engineer?” Opinions on this subject differed widely and it was decided that a pragmatic way to resolve the question of defining a materials professional was to refer to the COSMAT Committee itself, supplemented by other groups of knowledgeable scientists and engineers, including members of the technical staffs of the Bell Telephone Laboratories and the Ford Scientific Laboratories, university department heads, and members of the National Materials Advisory Board and of the Interagency Council on Materials. The operational device consisted of circulating the Specialties List from the National Register of Scientific and Technical Personnel and the National Engineers Register List of Areas of Technology and Science to the above groups. These lists were then used by respondents to describe their employment profiles and professional competences. All told, 96 useful responses were analyzed. As expected, a diversity of opinion among the respondents was found, but there was also considerable agreement. Thus, an MSE score (in essence, a measure of the percentage of respondents who believed that a specialty area properly belonged to the MSE field) was defined to describe quantitatively the degree to which each such area was regarded to be in the province of MSE.* The spectrum of scores so obtained ranged continuously from practically universal agreement on inclusion of some areas in MSE to general agreement that many other areas were clearly outside MSE. Obviously, there was a certain arbitrariness in our choice of where to draw the line bounding MSE for the purposes of this study. We usually adopted a cutoff score of 45, but will discuss on occasion how choice of a different score would have affected our results. The names of the specialties used and their MSE scores are given in Attachments 2A.1 (page 2–85) and 2A.2 (page 2–88).

The effect of increasing the stringency of the criterion for inclusion of a specialty field in MSE is shown in Figure 2.9. Here the percentage of all respondents to the 1968 and 1969 Registers who are to be included in MSE is plotted as a function of the MSE cutoff score—the higher the latter, the smaller the population included in MSE. Ideally, of course, the plot of Figure 2.9 should be a horizontal line; then all respondents to the poll would agree on the fields to be included in MSE, all fields would have an MSE score of 100 or 0, and the number of people in MSE would be independent of the cutoff score. The more nearly horizontal the line, the more nearly this ideal is attained.

Apparently, then, the ideal is more closely approached in the case of the Science Register than in the case of the Engineers Register. It is felt that the polling via the specialties lists is a more accurate and useful procedure for scientists than for the engineers because the specialties list used in the survey of scientists happened to be much more detailed and technically descriptive than the list of areas of technology and science used to survey the engineers.

The Engineers Register

The National Engineers Register List of Areas of Technology and Science was also circulated to a second group of specialists in materials engineering and a somewhat different set of rankings of the areas were obtained for inclusion in MSE. The most populous fields appeared high in both cases, however, and we believe that our profile of the materials engineer is not unduly affected by the choice of group polled or the exact cutoff point.

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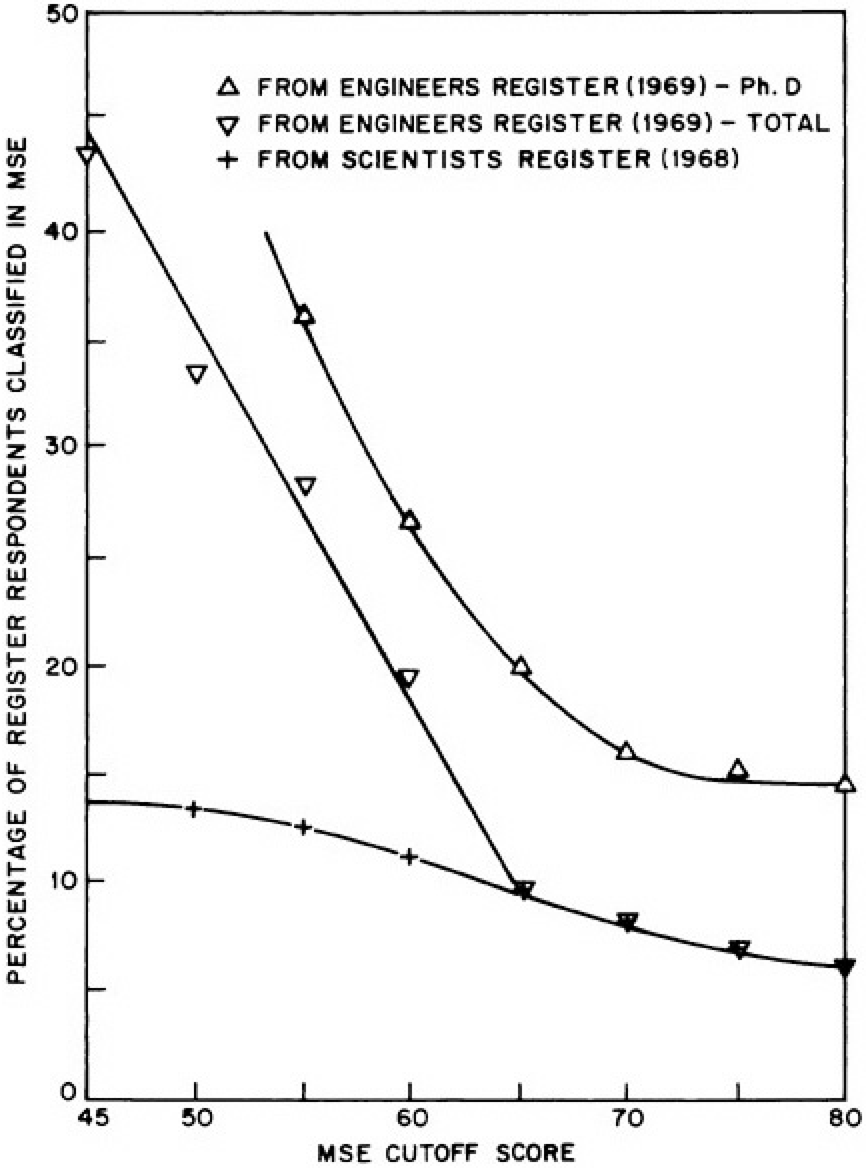
* Specifically, the MSE score for each specialty field was defined as $\text{MSE}=100\times([\text{in}]+0.5\times[\text{doubtful}])\div([\text{in}]+[\text{doubtful}]+[\text{out}])$, where [in] and [out] are the numbers of respondents to the poll who placed the field clearly inside or outside MSE, respectively, and [doubtful] is the number who felt it was on the fringe of MSE or were undecided.

FIGURE 2.9



PERCENTAGE OF REGISTER RESPONDENTS IN MSE vs MSE CUTOFF SCORE

Having identified a group of areas of technology and science to characterize MSE, surveys were made of the ways in which engineers in the Engineers Register, whose employment profile indicated that they were employed in one of these areas, responded to the various questions of the Engineers Register. The accompanying tables are based on these counts. In most instances, the results are described by percentages. In a few cases, however, it is most appropriate to present numbers of engineers. It must be remembered in such cases that the data represent only a relatively small sample of the engineering profession. The data on the Engineers Register used in this study refer to a population with a size equal to 6.9×size of our sample. The factor 6.9 then can be applied to estimate total numbers in the Register from the numbers presented in this study. The population registered by the Engineers Joint Council does not, however, include all engineers, but only those who are members of a society affiliated with EJC; it can be estimated that the total population of engineers is 3.5 times larger. Thus, rough estimates of total numbers of engineers can be obtained by multiplication by 24 (i.e. 6.9×3.5), although it must be emphasized that large errors can be made by application of this factor in detail, since engineers affiliated with EJC societies may not be typical of those not so affiliated.

In most instances, the figures for materials engineers are compared with similar ones for all engineers.* Furthermore, it turns out that there are striking differences in many respects between the Ph.D.'s in an engineering field and the nondoctoral engineers. Thus, although the doctoral engineers are few in number compared to the total engineers, results for them are tabulated separately.

Table 2.23 compares gross statistics, educational curricula, and type of employer of those identified as materials engineers with all engineers. A few salient observations concerning the differences may be made. Apparently, the larger areas or specialties of technology and science fall into the materials field, since, although only 29 percent of the specialties are included, these specialties contain about half of all of the engineers. The materials engineers, so defined, are slightly more highly educated than the average engineer; 8.8 percent of them have their Ph.D. as compared to 7.7 percent of all the engineers. There is a significantly smaller percentage of graduates from electrical curricula among the materials engineers, than among the total engineers. Metallurgical training is particularly prominent among the Ph.D.'s in the materials field. The materials engineers are slightly more concentrated in industry and business than the average engineer, and the reverse in the federal government.

Table 2.24 shows the leading societies represented among the materials engineers. These are the same societies that lead in membership among all engineers and in size of society, although there are some significant differences in the ordering of the societies among the different groups. The higher concentration of materials engineers in ASM and ASME and the lower concentration in IEEE as compared to all engineers are noteworthy.

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* See "A Profile of the Engineering Profession: A Report from the 1969 National Engineers Register," Engineers Joint Council and National Science Foundation, 1971.

TABLE 2.23 Comparison of Materials Engineers with All Engineers

	Materials Engineers	All Engineers
Total Number in Survey*	21879	44800
Percent Ph.D.	8.8	7.7
Areas of Technology and Science	58	200
Leading Curricula (all degrees [%])		
Electrical/Electronic	11.8	20.8
Mechanical	24.8	18.0
Civil	15.4	13.7
Chemical/Chemistry	10.0	8.9
Metallurgical	6.7	4.0
Leading Curricula (Ph.D. [%])		
Chemical/Chemistry	21.3	19.1
Metallurgical	16.1	10.2
Engineering Mechanical	9.5	6.1
Civil	9.8	8.6
Mechanical	13.7	11.0
Electrical/Electronic	6.9	11.0
Type of Employer (%)		
Industry and Business	75	72
Education and Non-Profit	9	7
Federal Government	7	10

* Multiply the numbers by 6.9 to obtain figures corresponding to the total number of registrants, and then by another factor of 3.5 to scale up to the total engineering population in the U.S.

TABLE 2.24 Society Membership (%)

Leading Societies	% Materials Engineers (Ph.D.) Who Are Members.	% Materials Engineers Who Are Members	% All Engineers Who Are Members
ASME	24.6	21.5	18
ASCE	13.0	17.1	18
IEEE	11.4	12.6	18
AIME	21.8	11.4	10
NSPE	6.6	11.3	11
ASM	18.6	10.6	5
AIChE	18.0	9.7	8
AIAA	16.3	7.2	11
ASEE	27.9	4.6	5

The differences among societies in percentage of Ph.D. materials engineers who are members as compared to percentage of all engineers and all materials engineers who are members is suggestive of differing degrees of sophistication in the use of materials in different segments of the engineering enterprise. Table 2.25 has been prepared to study this topic further. The Engineers Register arranges the areas of technology and science into "product groups." In Table 2.25 the percentage of Ph.D. level materials engineers that the COSMAT survey found in each large and well-defined product group is presented. The total number of materials engineers in each group is also given as an indication of the significance of the statistic. It will be seen that there are three kinds of product groups. One group comprises Construction and Civil Engineering, Machinery and Mechanical Equipment, and Utilities; Ph.D.'s constitute less than a percent of the materials engineers employed in this group. The second group, including Electrical Equipment, Transportation, and Motor Vehicle Transportation, contains a few percent of Ph.D.'s among its materials engineers. The third group, including Aircraft and Space, Ceramics, Chemicals, Computers, Electronic Equipment, and Basic Metals, employs of the order of 10 percent Ph.D.'s among its materials engineers.

It is also important to comment at this point on the way in which choice of sample affects the results of Table 2.24 and, perhaps, of other tables in this series. Only members of a limited selection of societies associated with the EJC are included in the list from which the EJC sample was drawn. There is naturally a tendency for membership in these societies to be emphasized in the results. A case in point is the Society of Plastics Engineers (SPE). Only 152 respondents to the Register indicated membership in SPE in the 1969 Survey. However, in a comparable survey in 1964, 952 memberships in SPE were reported by respondents. The difference is a reflection of the fact that the SPE membership list was included in constructing the 1964 sample.

On the other hand, the completeness with which our specialty selection does cover the materials areas among the engineers is illustrated by the following statistic; of 2380 respondents to the survey who indicated membership in the ASM, 2286 are included in our classification of materials engineers.

Table 2.26 presents the principal employment functions of materials engineers. It is seen that these are not very different from the functions of all engineers. A similar statement can be made about supervisory responsibilities of materials engineers; they are essentially the same as most engineers as a whole.

A question concerning professional identification revealed that materials engineers have a slightly more scientific orientation than engineers as a whole. 6.4 percent of materials engineers identified themselves with a scientific discipline (physicist, chemist, geologist, metallurgist) as compared to 4 percent of all engineers.

Table 2.27 shows that 37 percent of all materials engineers received some federal government support for their work. This is somewhat less than the percentage reported by all engineers, 45 percent. Table 2.27 also shows the national programs to which this support is related.

TABLE 2.25 Percentage of Ph.D.'s Among Materials Engineers by Product Group

Product Group	Number of Materials Engineers	Percent Ph.D.
Aircraft and Space	1779	9
Ceramics	234	11
Chemicals	1910	12
Computers	266	10
Construction and Civil Engineering	3726	0.3
Electrical Equipment	1246	3
Electronic Equipment	875	10
Machinery and Mechanical Equipment	3323	0.3
Transportation	301	3
Metals, Basic	1638	15
Metal Products	790	4
Motor Vehicle Transportation	756	2
Utilities	858	0.3

TABLE 2.26 Principal Functions of Materials Engineering (%)

	Materials Engineers		
	Ph.D.	All	All Engineers
Research	29.2	8.2	8
Teaching	33.7	5.3	5
Design	3.5	22.0	18
Planning, Directing	11.3	17.0	20
Development	9.4	9.3	9
Sales, Technical Services	0.8	6.8	6

TABLE 2.27 Materials Engineers Receiving Government Support (%)

Program	Ph.D. Materials Engineers	All Materials Engineers
All	53.1	37.3
Defense	26.3	18.6
Atomic Energy	12.7	5.4
Space	13.7	7.2
Public Works	0.9	5.2
Transportation	3.6	5.7

The product or service to which the work of engineers is related is presented in Table 2.28. Again, the materials engineer is similar to the other engineers, the notable exception being a heavier concentration of materials engineering in Machinery and Mechanical Equipment and in Basic Metals areas. The high concentration of Ph.D. materials engineers in educational services is also noteworthy.

Tables 2.29 and 2.30 indicate the areas of technology and science which contribute most of the members of our materials group. The amorphous character of the materials field may be seen by the vagueness with which many of the titles included describe the work of the engineer. Thus, the largest contributor to the statistics is simply called Engineering. The reason that our restricted set of areas includes half of the engineering profession is a result of the inclusion by the respondents to our poll of the various large, vaguely-defined fields, such as Engineering, Electrical Engineering, and Mechanical Engineering in the survey. It may be noted that the 12 areas listed in Table 2.29 account for about 80 percent of the materials engineers. These areas only account for about 40 percent of all engineers. Thus, sharp contrasts between materials engineers and the average engineer of the survey cannot be expected.

Because the total population of the areas of technology and science chosen to represent materials engineering is diluted with a substantial number of nonmaterials engineers, especially in the broadly inclusive areas such as “Engineering,” we also studied a more rigorously defined group of materials engineers, by counting responses for the 16 highest ranking areas of our poll. All these areas received MSE scores of 75 or greater on the poll of COSMAT participants; there is a large measure of agreement that they are part of materials engineering, and it can be stated with confidence that most of the individuals are indeed materials engineers. These areas are listed in Table 2.31.

It will be seen that these specialties, which are recognized by most of our respondents as belonging essentially to materials engineering, do not include the more vaguely-defined areas that contribute so much to the main group of materials engineers, and, indeed, of all engineers in the Register. We call the areas in Table 2.31 “agreed” materials engineering areas, but stress that materials engineers in other areas are equally materials engineers.

Selected characteristics of the engineers in the 16 high-ranking areas are shown in Table 2.32. A greater concentration of this “agreed” group in a few categories and more striking differences with engineers as a whole are revealed by comparison of Table 2.32 with previous tables. Tables 2.31 and 2.32 also show that these “agreed” specialties are mainly metallurgical. This is indicated not only by areas of technology in Table 2.31, but by the leading curricula, strong concentration of society membership in ASM and AIME, and by employment in metals-producing fields in Table 2.32.

It is also found that the employment of materials engineers in the selected 16 areas is slightly more-heavily concentrated in industry and business and in educational and nonprofit enterprises than is the average engineer. These materials engineers are also much more heavily oriented toward research than engineering as a whole, and less toward design, planning, and directing. Although the government support for the “agreed” areas is

TABLE 2.28 Product or Service Related to Employment (%)

	Materials Engineers		
	(Ph.D.)	(All)	All Engineers
Construction and Civil Engineering	5.7	17.0	16
Machinery and Mechanical Equipment	5.7	15.2	10
Chemicals and Allied Products	11.4	8.7	7
Aircraft and Space	8.7	8.1	11
Metals, Basic (except Mining)	12.5	7.5	4
Electrical Equipment and Services	2.2	5.7	7
Educational and Information Services	32.1	5.2	5
Electronic Equipment and Service	4.5	4.0	7

TABLE 2.29 Leading Employment Specialties of Materials Engineers (%)

Name	Number of Materials Engineers	Percent of All Materials Engineers
Engineering	3598	16.4
Mechanical Engineering	3375	15.4
Structures	1993	9.1
Electrical Engineering	1971	9.0
Product Engineering	1072	4.9
Electronic Applications	960	4.4
Instrumentation	909	4.2
Manufacturing Technology	780	3.6
Chemical Applications	778	3.6
Mechanical Applications, Applied Mechanics	697	3.2
Metallurgy (General)	657	3.0
Materials Applications	616	2.8
		79.6

TABLE 2.30 Leading Employment Specialties of Materials Engineers (Ph.D., [%])

Name	Number of All Ph.D. Materials Engineers	Percent of All Ph.D. Materials Engineers
Mechanical Engineering	175	9.1
Metallurgy, Physical	162	8.4
Structures	158	8.2
Engineering	153	8.0
Chemical Applications	135	7.0
Mechanics	119	6.2
Electrical Engineering	110	5.7
Heat Transfer	96	5.0
Metallurgy (General)	81	4.2
Processes	73	3.8
		65.6

TABLE 2.31 Some "Agreed" Areas of Technology and Science (MSE Score = 75) in Materials Engineering

Name
Metallurgy (general)
Metallurgy (physical)
Metallurgy (powder)
Materials Properties
Crystals, Crystallography
Materials Applications
Metallurgy (process)
Corrosion
Solid State
Casting
Metallurgy (extractive)
Thermodynamics
Coating, Plating, Cladding
Dielectrics
Forming, Shaping
Friction

TABLE 2.32 Characteristics of Materials Engineers in Sixteen "Agreed" Areas of Technology and Science in Materials Engineering

	Ph.D. Materials Engineers	Total Materials Engineers
Number	527	3135
Percent Ph.D.	—	16.8
Leading Curricula (percent)		
Metallurgical	52.9	39.8
Chemical/Chemistry	15.4	13.1
Mechanical	5.5	11.5
Type of Employer (percent)		
Industry and Business	53.5	78.2
Education and Nonprofit	37.2	12.0
Federal Government	5.7	5.2
Leading Societies (percent)		
ASM	57.9	52.8
AIME	65.3	42.9
ASTM	9.1	10.2
Principal Functions (percent)		
Research	42.1	21.3
Teaching	26.6	6.2
Planning, Directing	8.9	12.3
Development	7.8	11.8
Sales, Technical Services	0.9	11.2
Receiving Government Support		
Total	52.8	34.6
Defense	30.8	20.9
Atomic Energy	16.6	7.8
Space	13.9	10.5
Transportation	4.4	9.5
Leading Products or Service		
Metals, Basic (except Mining)	41.2	42.3
Machinery, Mechanical Equipment	2.7	8.8
Aircraft and Space	7.0	8.4
Metal Fabricated Products	3.4	6.4
Professional Identification (percent)		
Metallurgist	43.8	29.6
Physicist, Chemist, Geologist	8.0	3.3
Engineer	39.1	50.6
Other	6.9	13.5

about the same as for all engineers, it is more concentrated in the Defense, Atomic Energy, and Space fields than is the case for the average engineer. The scientific orientation of the 16 areas is also shown by the fact that only about half of their number identify themselves as engineers, in contrast to 85 percent of all those on the Register who identify themselves as engineers in response to a question concerning professional identification.

The Science Register

Our analysis of the Science Register was similar to that of the Engineers Register. A line between those regarded as materials scientists and those excluded was drawn at an MSE score of 45. Then, as in the case of the Engineers Register, a count of the responses to various questions by the materials science population was made.

The Science Register contained salary information, and, to investigate salaries, a five-dimensional table of the following variables was constructed: degree, age, salary, type of employer, work activity. Obviously, such a table contains tens of thousands of entries, and it is not feasible to reproduce it here. However, the data were available to COSMAT committees for their detailed studies and will form the basis for comments and tables in this section.

The treatment of the data for scientists is necessarily different than that for engineers since different questions were asked on the two Registers. Furthermore, the Register of Scientists is intended to be complete rather than a sample. It is, indeed, estimated that the coverage of Ph.D. scientists is quite complete, being at least 80 percent. On the other hand, the non-Ph.D. scientist group is less well defined because the criteria for inclusion in the Register vary from one participating society to another. Thus, COSMAT regards the results for the Ph.D. scientists as the most significant in the present study and it is these findings that will be emphasized.

The record provided by NSF to COSMAT containing information on all those scientists employed in one of the specialties identified as part of materials science covers about 42,000 scientists. (It will be observed that this is substantially less than the number of persons characterized as materials engineers.) Of the 42,000 materials scientists, 39 percent or about 16,500 have doctoral degrees. These numbers are not very sensitive to the exact score at which the line between materials science and other fields is drawn; they are not changed by more than 10 percent if a cutoff MSE score of 55 is used instead of 45.

A breakdown of the scientific disciplines in which the employment specialties of materials scientists are found, is given in Table 2.33. It is seen that most of the materials scientists are chemists and that the largest subfield of chemistry represented is organic chemistry. About half of all the chemists and 30 percent of all the physicists in the National Register are materials scientists by our criteria.

The heavy component of chemistry among those identified as materials scientists is shown in Table 2.34, which tabulates the leading major subjects of highest degree. This is confirmed by Table 2.35 where the leading professional identifications of the materials scientists are tabulated. Note that this table represents the response to an unstructured question; the

TABLE 2.33 Numbers of Materials Scientists, By Discipline

	Ph.D.	Percent	Total	Percent
Chemistry				
Analytical	1146	7.1	5014	12.1
Inorganic	1492	9.2	3328	8.0
Organic	4126	25.4	13271	32.0
Physical	3768	23.2	6437	15.5
Other Chemistry	610	3.8	3836	9.2
Total Chemistry	11142	69	31888	77
Physics				
Solid State	2211	13.6	3750	9.0
Other Physics	2619	16.1	5441	13.1
Total Physics	4830	29.8	9191	22.1
Earth Sciences	261	1.6	503	1.2
Total	16233		41582	

TABLE 2.34 Leading Major Subjects of Highest Degree Among Materials Scientists

	Ph.D.	Percent	Non-Ph.D.	Percent
Chemistry	4159	25.6	13551	32.6
Physics	3853	23.7	3628	8.7
Organic Chemistry	2539	15.6	878	2.1
Engineering	628	3.9	2518	6.1
Physical Chemistry	2211	13.6	515	1.2
Chemical Engineering	214	1.3	1522	3.7
Inorganic Chemistry	712	4.4	179	0.4
Analytical Chemistry	526	3.2	277	0.7

TABLE 2.35 Leading Professional Identifications of Materials Scientists

	Ph.D.	Percent	Non-Ph.D.	Percent
Chemist	2532	15.6	7047	17.0
Physicist	2853	17.6	2307	5.5
Chemical Engineer	550	3.4	3357	8.1
Organic Chemist	1908	11.8	1665	4.0
Physical Chemist	2084	12.8	979	2.4
Analytical Chemist	543	3.3	2048	4.9
Inorganic Chemist	649	4.0	489	1.2
Polymer Chemist	521	3.2	460	1.1
Solid State Physicist	537	3.3	282	0.7
Management Scientist	172	1.1	416	1.0

respondent was asked to write in what he considered himself to be. This, of course, limits the usefulness of the statistics. For example, it should not be assumed that everyone who simply wrote down “physicist” is not a solid-state physicist or that those who simply wrote down “chemist” are necessarily not polymer chemists.

Nevertheless, it may be interesting to examine the choice of professional identification among scientists whose specialties are clearly identified with aspects of materials science. Thus, Table 2.36 is presented, with the caution, again, that for example, not all rubber chemists necessarily characterize themselves by these words; they may simply have responded with “chemist” to the question concerning their professional identification.

The obviously low representation of certain fields that straddle science and engineering, for example, metallurgy, may be thought surprising. This is primarily a reflection of the selection of the cooperating societies that identify individuals for inclusion in the Science Register. A list of these societies is given in Table 2.37, and it can be seen that no metals or metallurgical society is included; metallurgical societies are affiliated with the Engineers Joint Council and are included in the sampling for the Engineers Register.

The important results of our cross-tabulation of materials scientists according to their work activity, type of employer, salary and age, are summarized in Tables 2.38 and 2.39. Table 2.38 shows the employment of materials scientists by degree level, institution, and work activity. Half of the Ph.D materials scientists and three-fourths of the non-Ph.D.’s are employed in business and industry. Educational institutions are the next largest employer. Practically all of the applied R&D scientists are employed in industry, and a large fraction of the basic research scientists work in industry also. Naturally, teaching is dominated by the educational institutions.

Table 2.39 shows median basic annual salaries (1968) of materials scientist by age and type of employer. Apart from educational institutions, there is little variation in salary among the various types of employer. There is also little variation with age, beyond the age of 40 or 45.

COSMAT also attempted to deduce the time dependence of some of the statistical aspects of materials science. Unfortunately, the list of specialties has changed from year-to-year to reflect the evolution of scientific fields, and thus no inclusive definition of materials science of the type developed for 1968 was available. As a result, studies like those carried out for the 1968 Register were not possible. A few names of materials science specialties that appeared on the specialties list in all of the years 1964, 1966, 1968, and 1970 and certain groups of specialties that might be expected to represent the same subject during these years were, however, selected. Unfortunately, the attempt cannot be regarded as successful; changes in the specialties list affect the population of specialties whose names are unchanged. For what they are worth, the results of populations of the sample specialty groups are listed in Table 2.40. Many curious changes will be noted, and COSMAT reemphasizes its view that these are almost certainly symptons of changes in the specialties list rather than changes in materials science.

TABLE 2.36 Number of Materials Scientists with Selected Professional Identification

	Ph.D.	Percent	Non-Ph.D.	Percent
Polymer Chemist	521	3.2	460	1.1
Rubber Chemist	12	0.1	312	0.8
Solid-State Physicist	537	3.3	282	0.7
Materials Chemist	68	0.4	261	0.6
Crystallographer	27	0.2	13	–
Cellulose Chemist	3	–	7	–
Textile Chemist	32	0.2	145	0.3
Ceramist	13	0.1	1	–
Polymer Specialist	14	0.1	10	–
Metallurgist	169	1.0	301	0.7
Materials Specialist	68	0.4	33	0.1
Mineralogist	60	0.4	45	0.1
Elastomer Chemist	3	–	26	–
Coatings Chemist	10	0.1	177	0.4
Paper Chemist	24	0.1	73	0.2
Corrosion Chemist	11	0.1	67	0.2
Solid-State Chemist	50	0.3	27	0.1
Electrochemist	119	0.7	168	0.4
Semiconductor Chemist	4	–	9	–
Plastics Chemist	26	0.2	230	0.6
Surface Chemist	43	0.3	27	0.1
Metallurgical Chemist	10	0.1	9	–

TABLE 2.37 Criteria for Inclusion in the Science Register

The cooperating societies identify individuals with “full professional standing” for inclusion in the Science Register, whether or not they are members of a professional society. The following criteria for “full professional standing” were established in 1968 by the societies:

CHEMIST (American Chemical Society) —A bachelor’s degree and current employment in an area of chemistry; or 10 years of professional experience in an area of chemistry.

EARTH OR MARINE SCIENTIST (American Geological Institute) —A bachelor’s degree in an area of earth or marine science; or professional identification of geological scientist; or current employment in earth or marine science; and either enrolled currently in a Ph.D. program or 1 year of professional experience.

ATMOSPHERIC OR SPACE SCIENTIST (American Meteorological Society) —A degree in the atmospheric or space sciences; or professional membership in the American Meteorological Society, or 10 years of professional service.

PHYSICIST OR ASTRONOMER (American Institute of Physics) —A bachelor’s degree with 2 years of additional training or work experience; or the equivalent in professional experience.

MATHEMATICIAN, STATISTICIAN, OR COMPUTER SCIENTIST (American Mathematical Society) —A bachelor’s degree in mathematics, statistics, or computer science with 4 years of professional experience; or a master’s degree with 2 years of professional experience; or a Ph.D.; or the equivalent in professional experience.

BIOLOGIST (American Institute of Biological Sciences) —A bachelor’s degree in an area of biology with 2 years of professional experience; or a master’s degree with 1 year of professional experience; or a Ph.D.; or the equivalent in professional experience,

BIOMEDICAL SCIENTIST (Federation of American Societies for Experimental Biology) —A Ph.D. in an area of human biology and engaged in research; or a professional medical degree and engaged in research; or the equivalent in professional experience.

PSYCHOLOGIST (American Psychological Association) —The completion of 2 years of graduate work in psychology and either employed in work or engaged in graduate study that is primarily psychological in character; or a master’s degree in psychology from a recognized graduate school with 1 year of professional experience; or a Ph.D. based in part upon a psychological dissertation and conferred by a graduate school of recognized standing; or the equivalent in professional experience.

TABLE 2.37 Criteria for Inclusion in the Science Register (Continued)

ECONOMIST (American Economic Association) —A bachelor’s degree in economics with 2 years of professional experience; or a graduate degree in economics; or the equivalent in professional experience.
SOCIOLOGIST (American Sociological Association) —A bachelor’s degree in sociology or closely related field with 2 years of graduate training and either currently employed in a sociological field or enrolled in a graduate school; or a master’s degree with either 1 year of professional experience or 1 additional year of graduate training; or a Ph.D.; or the equivalent in professional experience.
POLITICAL SCIENTIST (American Political Science Association) —A master’s degree in political science or 2 years of graduate work with 1 year of professional experience; or a Ph.D. in political science; or substantial professional achievement in political science; or the equivalent in professional experience.
ANTHROPOLOGIST (American Anthropological Association) —A Ph.D. in anthropology; or the equivalent in professional experience.
LINGUIST (Center for Applied Linguistics) —A bachelor’s degree in linquistics with evidence of continued activity in the field; or graduate training in linguistics; or employment in the field of linguistics; or professional identification of linguist supported by linguistic specializations; or the equivalent in professional experience.

Source: “American Science Manpower 1968,” A Report of the National Register of Scientific and Technical Personnel, National Science Foundation NSF 69–38, Appendix C, p. 265.

TABLE 2.38 Employment of Ph.D. Materials Scientists by Institution and Work Activity (1968)

	Basic Research	Applied Research	Development and Design	Management R & D	Management Other	Teaching	Total[b]
Educational Institutions	1858	91	3	119	182	2963	5377
Business and Industry	1758	2580	548	2202	310	2	7774
U.S. Government	533	132	12	182	8	5	905
FFRC[a]	515	218	18	127	4	6	917
Nonprofit	110	48	4	64	3	1	239
Total[b]	4875	3125	602	2736	524	2999	15517
Educational Institutions	736	100	37	17	29	327	1336
Business and Industry	786	3320	5479	2631	1766	9	16497
U.S. Government	412	563	371	253	83	0	1846
FFRC[a]	136	148	125	56	21	1	535
Nonprofit	64	96	21	36	8	5	245
Total[b]	2213	4338	6227	3070	1907	463	21319

[a] Federally funded research center.

[b] Total may exceed sum of entries because of provision for other minor categories.

TABLE 2.39 Median Basic Annual Salary of Ph.D. Materials Scientists by Age and Type of Employer (1968) ($1,000)

	Educational Institution	Business-Industry	United States Government	FFRC	Non-Profit	All	Number
25–29	9.1	14.6	11.9	13.8	14.0	12.0	1937
30–34	10.8	15.5	13.6	15.6	15.0	14.1	3526
35–39	12.6	17.2	16.4	17.8	16.8	16.1	3265
40–44	15.3	19.0	18.1	18.7	18.4	18.0	2470
45–49	17.1	20.0	19.2	20.1	19.5	19.3	1894
50–54	18.0	21.1	20.4	20.5	20.0	20.2	1109
55–59	18.1	20.8	20.2	20.2		19.8	672
60–64	17.6	20.3	21.5			19.8	431
65–69	18.0	20.2	18.2			18.8	155
Number	5377	7774	905	917	239	15517	

TABLE 2.39 Median Basic Annual Salary of Non-Ph.D. Materials Scientists by Age and Type of Employer (1968) ($1,000)

	Educational Institution	Business-Industry	United States Government	FFRC	Non-Profit	All	Number
Under 25	4.4	8.8	8.8			8.3	830
25–29	5.1	10.2	10.6	10.1	9.0	9.7	3862
30–34	8.6	11.8	12.5	11.8	11.5	11.7	3300
35–39	9.7	13.4	13.1	13.7	12.4	13.2	3041
40–44	11.2	14.4	13.9	15.0	13.8	14.3	3280
45–49	12.7	15.3	14.9	15.6	14.0	15.2	2924
50–54	11.9	15.9	15.0	15.2	16.7	15.6	2122
55–59	11.6	15.5	15.4			15.4	1190
60–64	13.0	15.6	14.9			15.1	576
65–69	14.0	14.2				14.2	109
Number	1336	16497	1846	535	245	21319	

TABLE 2.40 Number of Materials Scientists in Specialty Areas from 1964 to 1970

	Register Years			
Topical Group	1964	1966	1968	1970
Minerals and Natural Materials	327	376	503	468
Coatings	1361	1322	1512	1404
Polymers	7161	6908	8363	5478
Crystallography	161	197	320	351
Catalysis	401	666	800	590
Corrosion	224	266	360	355
Solid State	3379	3837	3750	5331
Total	13014	13572	15609	13977

Total Number of Materials Scientists and Engineers

The above analysis has been directed toward characterization of materials scientists and engineers, that is, answering the question: Who are the materials scientists and engineers. A natural, related question is: How many are there? The answer to this question is, like the question of characterization, beclouded by the lack of unanimity as to who should be counted as a materials engineer or scientist. Further uncertainties in the total number are also introduced by the fact that the Registers on which our study is based only include a sample of the professions. In the case of scientists, it is reliably estimated that about 3/5 of all scientists are included in the Science Register so that reasonable estimates of total science population can be obtained by multiplying by a factor 5/3. Much greater uncertainty exists in the case of total engineers. It is estimated there are 1.0–1.2 million engineers in the U.S. 308,000 of these are included in the EJC list from which the sample for the Engineers Register was drawn. There is little basis, however, for assuming that these 308,000 are typical of the total population of engineers. The sample included in the Engineers Register consists of 44,000 engineers or 1/24 of the total number of engineers in the country so that the correct total number can be obtained by multiplying by 24, but it must be understood that serious distortions of the characteristics of engineers can be introduced by multiplication by this large factor.

Still another question that must be faced in connection with the Engineers Register concerns the ill-defined nature of many of the areas of science and technology that are presented to respondents to the Engineers Register. As mentioned earlier, the names of these areas do not always clearly indicate whether the respondent is a materials engineer or not, and it is necessary to make some estimate of the fraction of the materials engineers in the various areas, notably the large areas listed in Table 2.29. Obviously, this can only be done very crudely. The best estimate of COSMAT is that about 40 percent of the engineers in the EJC sample are materials engineers. Application of this 40 percent figure to the 1.1 million engineers in the country suggests a total of 450,000 materials engineers. We further estimate that 40,000 of the materials engineers are metallurgists and 10,000 are ceramists—leaving about 400,000 other materials engineers. These totals and totals for the materials scientists are presented in Table 2.41.

TABLE 2.41 Estimated Total Number of Materials Scientists and Engineers in the United States

Ceramists	10,000
Metallurgists	40,000
Other Engineers	400,000*
Physicists	15,000
Chemists	50,000
TOTAL	515,000

* On a full-time equivalent basis, the 400,000 engineers shown here would be reduced to 200,000 approximately. The other figures in this table are already full-time equivalents, making the total MSE manpower in the U.S. equal to 315,000.

ATTACHMENT 2A.1 Specialty Areas in the 1969 National Engineers Register with MSE Score Greater Than 45

Specialty Area			MSE Score
I.	Metallurgical Group		—
	1.	Metallurgy, general	100
	2.	Metallurgy, physical	99
	3.	Metallurgy, powder	98
	4.	Metallurgy, process	92
	5.	Metallurgy, extractive	82
	6.	Casting	82
	7.	Welding	74
	8.	Benefication, ore processing	59
II.	Chemical and Materials Group		—
	1.	Materials properties	96
	2.	Crystals, crystallography	94
	3.	Materials applications	93
	4.	Corrosion	90
	5.	Coating, plating, cladding	79
	6.	Filament technology	68
	7.	Thermochemistry	68
	8.	Electrochemistry	62
	9.	Fuel cells	58
	10.	Chemical applications	55
III.	Heat, Light, and Applied Physics Group		—
	1.	Solid state	87
	2.	Thermodynamics	80
	3.	Insulation, thermal	74
	4.	Thermophysics	70
	5.	High temperature	68
	6.	Physics	65
	7.	Applied physics	63
	8.	Cryogenics	58
	9.	Ultrasonics	53
	10.	Heat transfer	51

Specialty Area			MSE Score
IV.	Engineering Process and Application Group		—
	1.	Forming, shaping	76
	2.	Fastening, joining	70
	3.	Materials handling	62
	4.	Refining	57
	5.	Processes	45
V.	Work Management and Evaluation Group		—
	1.	Nondestructive tests	70
	2.	Testing, laboratory	61
	3.	Radiography, x-rays	54
	4.	Specifications, standards	49
	5.	Product engineering	43*
	6.	Production methods	43*
	7.	Quality control	41*
VI.	Dynamics and Mechanics Group		—
	1.	Friction	75
	2.	High pressure	66
	3.	Lubrication	60
	4.	Vacuum technology	57
	5.	Kinetics	54
	6.	Mechanical applications	54
	7.	Mechanics	51
	8.	Mass transfer	49
	9.	Propulsion	49
VII.	Electromagnetic Group		—
	1.	Dielectrics	79
	2.	Magnetics, magnetism	74
	3.	Insulation, electrical	73
	4.	Superconductivity	72
	5.	Photoelectricity	52
	6.	Electronic applications	51
	7.	Electrical applications	43*

* These specialties were regarded as sufficiently important to be included even though their MSE scores were somewhat below 45.

Specialty Area			MSE Score
VIII.	Environmental and Structural Group		—
	1.	Concrete technology	69
	2.	Structures	55
	3.	Rock mechanics	48
	4.	Solid waste	47
IX.	Automation and Control Group		—
	1.	Instrumentation	51
X.	Information Mathematics		—
	1.	Stress analysis	68
	2.	Mathematics	48

ATTACHMENT 2A.2 Specialty Areas in the 1968 National Register of Scientific and Technical Personnel with MSE Score Greater Than 45

Specialty Area			MSE Score
I.	Atmospheric, Earth, Marine, and Space Sciences		—
	A.	Geochemistry	
		1. Mineral synthesis and stability relations of minerals	66
	B.	Geology	
		1. Mineralogy and crystallography	77
	C.	Solid-Earth Geophysics	
		1. Physical properties of natural materials	77
II.	Chemistry		—
	A.	Analytical	
		1. Electron microscopy	91
		2. Mass spectroscopy	77
		3. Fluorimetry, phosphor imetry, and infrared and Raman spectroscopy	74
		4. Magnetic resonance spectroscopy	74
		5. Electrochemical analysis	67
		6. Spectrochemical analysis	66
		7. Absorption spectroscopy	64
		8. Microchemical analysis	64
		9. Neutron activation	63
		10. Chemical microscopy	61
		11. Chromatography	58
		12. Extraction analysis	50
		13. Nucleonics and radiochemistry	49
	B.	Inorganic	—
		1. Inorganic materials useful as solid-state electronic devices, semiconductors, etc.	99
		2. Structure of inorganic compounds, crystallography, spectroscopy, etc .	94
		3. Inorganic polymers	91
		4. Synthesis of inorganic materials	91
		5. Boron and silicon compounds; asbestos, clay, glass, etc.	89

Specialty Area			MSE Score
	6.	Equilibrium and thermo dynamic relationships in inorganic systems	89
	7.	Theoretical inorganic chemistry, ligand field theory, molecular orbital theory, ionic model, theory of metals, etc.	82
	8.	Electropositive elements and their compounds (alkalies and alkaline earths, building products, etc.)	80
	9.	Mechanisms of inorganic reactions; reaction kinetics	79
	10.	Transition elements	79
	11.	Inner transition elements	70
	12.	Coordination compounds	68
	13.	Electron deficient compounds; boron hydrides, metal alkyles, etc.	64
	14.	Organometallic compounds	60
	15.	Nonmetals; halogen, oxygen, and nitrogen families; high-energy oxidizers	53
	16.	Nuclear chemistry and radio chemistry	52
	17.	Hydrogen and hydrides, high-energy fuels	50
C.	Organic		—
	1.	Polymers	92
	2.	Protective coatings	88
	3.	Plastics and synthetic resins	85
	4.	Rubber	85
	5.	Elastomers and related products	80
	6.	Wood, paper, cellulose	74
	7.	Adhesives	72
	8.	Cellular plastics	71
	9.	Nuclear magnetic resonance	68
	10.	Transition and noble metals in synthesis, catalysis, etc.	65
	11.	Mass spectroscopy	63
	12.	Reaction mechanisms, additions, eliminations, substitutions	63
	13.	Organometallics; boron, aluminum, tin, lead, etc.	61
	14.	Reaction mechanisms; rearrangements	61
	15.	Textiles and related products	57
	16.	Structure of organic molecules	55

Specialty Area			MSE Score
	17.	Organometallics; alkali and alkaline earth derivatives	52
	18.	Fluorine compounds	50
	19.	Organosilicon chemistry	45
D.	Physical		—
	1.	Crystallography	98
	2.	Polymers in bulk; morphology, phase transitions, rheology, and mechanical properties	95
	3.	Solid-state chemistry	91
	4.	Chemical and phase equilibria	88
	5.	Thermodynamics and thermochemistry	85
	6.	Catalysis and surface chemistry	83
	7.	Electrochemistry	82
	8.	High-temperature chemistry	82
	9.	Molecular structure	78
	10.	Energy transfer and relaxation processes	74
	11.	Quantum and valence theory	72
	12.	Statistical mechanics	71
	13.	Fused salts	69
	14.	Chemical kinetics; liquid phase	61
	15.	Colloid chemistry	60
	16.	Liquid state and solutions; electrolytes and non-electrolytes	59
	17.	Molecular spectroscopy	58
	18.	Ion exchange and membrane phenomena	57
	19.	Nuclear and radiochemistry	57
E.	Others in Related Chemical Specialties		—
	1.	Materials	100
	2.	Metallurgy	100
	3.	Corrosion and preservation	87
	4.	Adsorption and absorption	65
	5.	Electrochemical operations	64
	6.	Mass transfer	58
	7.	Mechanical separation	55
	8.	Instrumentation	54
	9.	Measurement and control	53
	10.	Quality control and standards	51
	11.	Chemical separation	49

Specialty Area				MSE Score
		12.	Heat transfer	49
		13.	Mixing	48
III.	Physics			—
	A.	Acoustics		
		1.	Mechanical vibrations and shock	56
	B.	Atomic and Molecular Physics		—
		1.	Chemical bonds and structure	88
		2.	Electron paramagnetic resonance	74
		3.	Molecular structure and spectra	72
		4.	Nuclear magnetic resonance	70
		5.	Mass spectroscopy	63
		6.	Atomic structure and spectra	62
		7.	Impact and scattering phenomena	51
		8.	Atomic, ionic, and molecular beams	46
	C.	Electromagnetism		—
		1.	Electron microscopy, ion optics	81
		2.	Magnetism	81
		3.	X-ray phenomena	72
		4.	X-ray technology	72
		5.	X-ray interactions	65
		6.	Physical electronics	51
		7.	Quantum electronics	61
		8.	Masers and such devices	59
	D.	Electronics		—
		1.	Semiconductor devices	47
		2.	Solid-state electronics	47
	E.	Mechanics		—
		1.	Elasticity	87
		2.	Friction	81
		3.	High-pressure physics	76
		4.	Impact phenomena	69
		5.	Instruments and measurements	60

Specialty Area			MSE Score
F.	Nuclear		—
	1.	Radiation effects	63
	2.	Radioactive materials, isotopes	52
G.	Optics		—
	1.	Properties of thin films	92
	2.	Optical materials	83
	3.	Spectroscopy	68
	4.	Lasers	65
	5.	Infrared phenomena	54
	6.	Fiber optics	51
H.	Fluids		—
	1.	Rheology (including plastic flow)	89
	2.	Transport phenomena, diffusion	75
	3.	Structure and properties of fluids	61
	4.	Viscosity	52
I.	Solid State		—
	1.	Ceramics	100
	2.	High polymers and glasses	99
	3.	Dislocations and plasticity	98
	4.	Semiconductors	96
	5.	Cooperative phenomena	94
	6.	Thin films	94
	7.	Electrical properties of surfaces and junctions	92
	8.	Lattice effects and diffusion	92
	9.	Dielectrics (including fluids)	91
	10.	Dynamics of crystal lattices	91
	11.	Ferromagnetism	91
	12.	Internal friction	89
	13.	Optical properties	88
	14.	Piezoelectricity and ferroelectricity	88
	15.	Surface structure and kinetics	88
	16.	Thermal conduction in solid state	87
	17.	Paramagnetism and diamagnetism	86
	18.	Quantum mechanics of solids	84
	19.	Radiation damage	84

Specialty Area			MSE Score
	20.	Luminescence	82
	21.	Superconductivity	82
	22.	Photoconductivity and related phenomena	81
	23.	Electron emission	80
	24.	Photoelectric phenomena	80
	25.	Resonance phenomena	80
J.	Thermal		—
	1.	Thermodynamics	82
	2.	Thermal properties	82
	3.	Thermodynamic relations, equations of state	79
	4.	High-temperature physics	69
	5.	Thermodynamic tables	67
	6.	Low-temperature physics	66
	7.	Calorimetry	66
	8.	Heat transmission	61
	9.	Temperature and its measurement	55
K.	Other Physics Specialties		—
	1.	Physical metallurgy	100
	2.	Physical properties of materials	100
	3.	Quantum mechanics	61
	4.	Mössbauer effect	60
	5.	Statistical mechanics	60
	6.	High-vacuum techniques	59
	7.	Constants, standards, units, metrology, conversion factors	58
	8.	Energy-conversion problems	54
	9.	Kinetic theory	50

CHAPTER 3

MATERIALS SCIENCE AND ENGINEERING AS A MULTI DISC IP LINE*

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* This chapter draws heavily on the work of COSMAT Panel II, and of its chairman, Richard S.Claassen in particular, and also on the work of Daniel C.Drucker and N.Bruce Hannay of Panel V.

CHAPTER 3

MATERIALS SCIENCE AND ENGINEERING AS A MULTIDISCIPLINE

MATERIALS, THE MATERIALS CYCLE, AND THE ROLE OF MATERIALS SCIENCE AND ENGINEERING

Materials are ubiquitous, so pervasive we often take them for granted. Yet they play a central role in much of our daily lives, in practically all manufacturing industries, and in much research and development in the physical and engineering sciences. Materials have a generality comparable to that of energy and information, and the three together comprise nearly all technology. For COSMAT purposes, we define materials as substances having properties which make them useful in machines, structures, devices, and products.

It is useful to depict a global materials cycle, shown in the Frontispiece. The earth is the source of all materials as well as the ultimate repository. Minerals and oils are taken from the earth, and trees and vegetable materials are harvested. Through beneficiation, purification, refining, pulping, and other processes these raw materials are converted into useful industrial materials—metals, chemicals, paper, for example. In subsequent processing, these bulk materials are modified to become engineering materials aimed at meeting performance requirements. The engineering materials are then fashioned by manufacturing processes into shapes and parts which are assembled to make a useful end-product. The product, once its useful life has finished, is eventually returned as waste to the earth, or it undergoes dismantling and material recovery to provide basic materials to feed into the materials cycle again.

The materials cycle thus divides naturally into two sections: the left-hand (materials supply) side is primarily concerned with obtaining industrial materials, whether from the earth or by reclamation, and from a knowledge viewpoint is generally within the province of the mineral, earth, and forestry technologies; the right-hand (materials consumption) side is primarily concerned with the uses of industrial materials in the manufacture of structures, devices, and machines, and their subsequent performance. Again, from the knowledge viewpoint, this side of the cycle is the main arena for materials science and engineering, the subject of this report. However, as the diagram clearly brings out, there is intimate interdependence among all stages of the overall materials cycle. The diagram also portrays the role of recycling—any way which enables materials to keep circulating in the right-hand side of the diagram reduces the demand for new raw materials from the earth in the left-hand side.

Any step taken in any part of the materials cycle may have repercussions elsewhere in the cycle. New paths around the cycle are continually being opened up through researches which lead to new materials, new applications, and thereby new demand and consumption patterns for materials. Furthermore, the materials cycle is not an isolated entity: every stage of the cycle consumes energy and can affect the environment. Increasingly, therefore, it is necessary for the specialist in MSE to consider the effects of technological changes on the complete system of the total materials cycle, including energy consumption and environmental quality.

INNOVATION IN MATERIALS SCIENCE AND ENGINEERING

MSE has become a basic instrument in bringing about technological changes. Discoveries of new materials and improvements to old ones—all undergirded by deeper understanding of the intimate relations between the processing, composition, and structure of materials on the one hand, together with their properties and function on the other—lead repeatedly to higher performance and efficiency in existing technologies (e.g. improved process for extracting titanium) and to the creation of new ones (e.g. silicon and the solid-state electronic industry). By the same token, a breakthrough in understanding the physics and chemistry of biocompatibility of synthetic materials could have a dramatic effect on the prosthetics industry.

MSE is both creative and responsive. New insights gained, often unexpectedly, through research on the properties and phenomena exhibited by materials can lead through development and engineering stages to new products and applications of benefit to mankind. But often it is the perception of some potential market or societal need for a product that stimulates the appropriate engineering and development and, in turn, the support of considerable applied and even basic research.

Whether MSE is operating in a creative or a responsive mode, it is having a technological and social impact at a very basic level. Materials as such are usually not very visible to the public that is primarily concerned with end-products and tends to take materials for granted. Yet materials are the working substance of all hardware used in all technologies and are crucial to successful product performance. Between the introduction of materials and the final product, there are often numerous manufacturing stages where extra value is added. Thus, an improved or new material may be decisive in determining the success, usefulness, or social value of a product, even though the cost of the material or the improvement might be very modest compared with the total product or social value. In this sense, materials can frequently be said to exert high economic leverage. Color TV has been made possible by the development of special phosphors; synthetic fibers, such as nylon and dacron, have made drip-dry apparel possible. There are also instances of low leverage in which materials improvements, while useful, do not exert such an enormous change in the end-product or in social patterns; such an example might be the change in steel used for making cans. Materials, and industries devoted completely to them, may represent about one-fifth of the Gross National Product, but without them there would be no Gross National Product.

Materials are often looked upon as relatively unspecific media which may find their way into a great variety of end-products. New materials or improved ones may lead to a whole variety of end-products involving widely different industries. For example, fiberglass lends itself for use in pleasure boats, as housing construction material, and as automobile bodies. Hence, materials can be said to have a relatively high degree of proprietary neutrality. One consequence of this situation is that materials research often forms a more neutral, yet broadly applicable, base for governmental support and cooperative ventures among companies than does research in various end-product technologies.

Besides the direct application of MSE to technology, innovation in the field can have important consequences for materials demand and consumption patterns, the consumption of energy, and the quality of the environment. MSE can play a vital role in meeting man’s needs for better transportation equipment, prosthetic devices, and the generation, transmission, and storage of energy. But by wreaking such technological changes, it can often change drastically the need or consumption patterns for materials and energy. New materials made from more abundant raw materials can often be developed as substitutes for old ones made from scarcer or ecologically less desirable raw materials; new ways can often be found for performing needed technological functions, e.g. transistors have replaced vacuum-tube triodes as basic amplifying elements in electronic circuits, and in more recent years integrated circuits replaced boxes of complex electronic equipment made up of many components. Looking ahead with another example, present work in certain forms of levitated ground transport, if successful, could lead to greatly increased demands for new magnetic or superconducting alloys. Or again, development of suitable catalysts based on relatively abundant materials could significantly reduce demand for platinum catalysts for treating automobile exhaust gases and for use in chemical processes.

As regards energy-consumption patterns, MSE has much to contribute in all phases—making new forms of generation possible, e.g. by finding solutions to the problem of fuel swelling under radiation damage in nuclear reactors; enabling new forms of electrical power distribution, e.g. through superconducting or cryogenic transmission lines; finding more efficient ways to store energy, e.g. through solid electrolytic batteries or fuel cells; and through finding more efficient ways of using and conserving energy, e.g. in more efficient materials-processing and manufacturing operations, and in the development of better thermal insulation materials.

Concerning environmental quality, MSE has much to contribute in finding, for example, cleaner materials processes, effective uses for waste materials, materials and designs more acceptable from the consumer viewpoint, and in developing instrumentation to monitor and control pollution.

Thus, innovation in MSE can play a significant role in the economy, in raising the standard of living, in minimizing demands for energy, in improving environmental quality, and in reducing demands for imported materials with a consequent favorable impact on the U.S. international trade balance. In the remainder of this chapter, therefore, a detailed examination will be made of the nature and scope of MSE and the factors that influence its potency as a multidiscipline.

CHANGING CHARACTER OF MATERIALS TECHNOLOGY

Science-Intensive and Experience-Based Technologies

Historically man has made use of materials more-or-less readily available from nature. In this century, however, he has repeatedly demonstrated an ability to synthesize radically new materials to meet increasingly complex and demanding requirements, an ability which so often depends on the latest in scientific knowledge. In fact, so successful has MSE been in recent years that designers and engineers have increasingly come to feel that somehow new materials can be devised, or old ones modified, to meet all manner of unusual requirements.

In the past, remarkable progress has been made in utilizing materials based on empirical knowledge of their properties and behavior related to their source and subsequent treatment. Many of the important alloys and ceramics were initially developed in this way. This approach is still invaluable and widely practiced. Graphite is a recent example of a material which has solved important problems in missiles where it forms rocket nozzles and as structural components in nuclear-power reactors. Yet, the necessary development was achieved by an enlightened empirical approach in a company which was very much material-source oriented. Graphite is a most complex material whose physical properties depend on the nature and processing of raw materials, on the quality of the initial carbon-containing material, on binder pyrolysis, and on a variety of processing variables. The most practical approach to development of a special graphite to withstand high temperature and pressure was a systematic study, therefore, of the dependence of properties on processing parameters. The starting point was an initial observation that hot pressing of normal-density carbon yielded a body of high density and high strength. Science was able to provide only a very general framework for the planning and execution of this program.

This important graphite development also illustrates a governing feature of the historical mode in materials development. Without a complete science framework and lacking a few broad unifying concepts, the practitioner in graphite development necessarily needed to know a very large collection of facts based on past experience in graphite. For that reason, he was material-source oriented and tended to be more affiliated with the material supplier than with the material consumer.

In recent decades, the interest in materials properties has been broadened from that of the supplier to include that of the consumer. In some programs, such as space and the solid-state electronics industry, the material user cannot meet all his objectives with presently existing materials. This, in turn, has often caused the user to become interested in the discovery and development of completely new materials. It has also caused a closer working relationship to be established between the material developer and the material user. Further, the programs which have run into materials limitations of the kind that determine success or failure are, in general, those which are straining for the utmost out of sophisticated science and technology generally. It has, therefore, been natural for the people involved to expect materials development likewise to utilize scientific contributions when available.

At the same time that the material users have been entering into materials development, the underlying knowledge and understanding in solid-state physics and chemistry has advanced tremendously. These two sciences have evolved several unifying concepts which reach across many materials and now provide common guidance to what seemed previously like disconnected problems in materials development.

Advances of fundamental understanding and the ability to design materials properties to exacting specifications have been most marked in the case of electronic materials. In other areas, our level of fundamental understanding is a long way from enabling us to design materials to withstand new uses and environmental conditions without considerable trial and error. Far from nearing saturation, fundamental understanding of the properties of the vast majority of materials and the consequent ability to develop new materials to specifications has barely begun.

The term science-intensive technology is used to designate those activities in which specific performance is at a premium and in which the generation of new fundamental understanding of materials is necessary before the desired performance can be achieved. Thus the descriptor, science-intensive technology or high technology, usually denotes an emerging area where knowledge and practice are changing rapidly and where there has not yet built up a widely based fund of experience and practical knowledge.

A familiar example to illustrate high technology is the space program where it is mandatory that a component must function in the desired manner at the proper time. Because the entire success of an expensive mission may depend upon the proper functioning of this component it is natural to expend whatever R & D is required to assure success. The actual cost of the materials making up the component becomes a secondary consideration. Another example is found in nuclear-power reactors. Fuel cladding must be of sufficient integrity to guarantee against hazardous release of radioactive byproducts. In the design and fabrication of the fuel cladding, considerable effort at a sophisticated scientific and engineering level is justified to achieve safety goals. In the solid-state electronics industry, we find an example where highly sophisticated and costly effort on materials is justified in terms of the overall product value—both the processing of semiconductor material and the assembly into discrete devices or integrated circuits requires a degree of control which would be unbelievable in most industrial situations.

The term experience-based technology, or low technology, is used to refer to programs which are not science intensive—in other words, which rely on more empirical approaches or which may be highly forgiving of manufacturing and processing variations. Typically, large material quantities are involved so that unit material costs are important. Examples are the manufacturing of dishes and structural steels; many tires are assembled in traditional ways involving much hard work; conventional approaches prevail in the construction of roads and highways where unit cost is of great importance; and the paper industry continues to use long-standing, empirically-derived processes.

Relative Pace of Innovation

There is a familiar pattern in the growth, development, and diffusion of a technology. At the birth and in the early stages of a new technology, such as solid-state electronics or nuclear-power reactors, the pace of invention is high and the innovating company or nation may well achieve a commanding position in the market for its new technology. In this premarketing stage, cost is of secondary importance, or rather it is an administrative decision related to some perception of the eventual pay-off. Later, the inventive pace begins to slacken while, at the same time, other companies or nations with the necessary educational level and technical competence are acquiring the knowledge and skills to catch up. The formerly commanding position of the original innovator is gradually eroded as the relevant technological capability diffuses nationally and internationally. In this stage, where the technology is termed as becoming mature, commercial advantage is kept by, or passes to, that company or nation that can most effectively minimize production and marketing costs while safeguarding the integrity of the product. Process innovation can then assume more importance than further product innovation.

The early stages of a technology, when the inventive pace is high, are often science-intensive, and are commonly referred to as “high technology.” It seems that high technologies in which the U.S. has been in the forefront, such as aerospace, computers, and nuclear reactors, have also been generally associated with international trade surpluses for the U.S. In the more mature stages, the science content of further developments in the technology can then be referred to as experience-intensive or “low technology.” Such technologies may be assimilated by developing countries, and are more likely to be associated with shifts in trade balance since the latter countries usually enjoy lower costs, primarily through lower labor rates. When a technology reaches this phase, the U.S. runs the risk of becoming quite dependent for further developments in that technology on foreign enterprise. This may be acceptable for some technologies but not for others critical to national economic and military security. The primary metals industries are prime examples of such experience-intensive technologies facing very severe foreign competition. Other industries in which technological leadership may have been lost by the U.S. are tires and various consumer goods such as shoes and bicycles. Still other technologies, some of which are regarded as high technologies, are moving in the same direction, e.g., automobiles, consumer electronics, and certain aircraft products.

The implications for materials technology in the U.S. in order to meet foreign competition and maintain viable domestic industries are that high inventive pace must be created or maintained in certain fields so as to create new high technologies and safeguard existing ones, and that the technological level must be raised and production costs lowered in selected, critical, mature industries. This must be done within the structure of U.S. industry which can be roughly classified, for our purposes, into the materials-producing and the materials-consuming industries. The former tend to be experience-intensive, while high-technology industries tend to fall in the latter category. The high-technology industries, if their commercial bases are sufficiently large, are more accustomed to maintaining a balanced, although product-oriented, R & D effort than are the low-technology industries.

Disciplinarity, Interdisciplinarity, and Multidisciplinarity

In the materials field, universities have evolved in the past along disciplinary lines—physics, chemistry, metallurgy, ceramics, and so on. Similar segmentation is apparent in the industrial sphere, some industries specializing in metals, others in ceramics, in glass, in chemicals, or in crystalline materials for electronics. In addition, there has tended to be segregation in another direction, between materials science on the one hand, embracing the traditional scientific disciplines, and materials engineering on the other, embracing those parts of the engineering disciplines concerned with developing processes and applications for materials.

Such separations are practical only when the technical objectives, scientific or engineering, are relatively simple or straightforward. For example, metallurgists may have the requisite knowledge to cope with the problem of developing improved alloys for use as electrical conductors. In such cases, the traditional, disciplinary approach can be adequate for pursuing a problem from the research phase to the production phase. But nowadays the trend in technology is towards ever more complex performance requirements, product and device designs, and dependence on more sophisticated knowledge of the physical phenomena that characterize an increasing diversity of materials. The areas of knowledge required to develop, say, an integrated circuit or a biomedical material are not at all coincident with the traditional disciplinary boundaries. It is obvious that many complex technologies call for knowledge and skills that may cut across several disciplines, including science and engineering. Thus, we see an increasing need for interdisciplinary approaches in order to achieve technical objectives.

But the interdisciplinary mode is by no means limited to applied research and development programs. This is also happening in basic materials research. The very core of materials science, the relation of properties to structure and composition, implies a need for the combined efforts of physicists, metallurgists and chemists, etc. In the past the physicist has too often made unrealistic assumptions about the composition, purity, and quality of the materials of his researches; the metallurgist has too often not understood sufficiently how the physical phenomena exhibited by a solid relate to its structure and composition.

We believe that materials research provides a natural meeting-ground for specialists from the various scientific and engineering disciplines, from basic research to applied research, development and engineering, and that the pressure for such interdisciplinary collaboration will grow in the future. It is vital, therefore, to establish the factors that are conducive to effective interdisciplinary materials research.

The field of MSE, broadly speaking, constitutes a multidisciplinary matrix of those disciplines which are related through the structure/property/processes/function/performance linkage of materials. At times, these disciplines are only loosely coupled and interact mainly through the diffusion of knowledge. But frequently, these disciplines are purposefully coupled together in various combinations in order to meet an objective; such groupings are defined as interdisciplinary. It will be shown that the multidiscipline of MSE has proved eminently effective as a medium for many clusters of interdisciplinary activity.

DEFINITION OF MATERIALS SCIENCE AND ENGINEERING

Many forces have served to shape the multidisciplinary field which has become known as materials science and engineering.

In the first place, MSE has come to be regarded as central to the industrial materials used for machines, devices, and structures.

Second, there is growing awareness of the integral role played by materials in the general fabric of society and of the increasingly sophisticated demands made on materials by complex technologies.

Third, this increasing recognition of the importance of materials is coupled with a growing appreciation of the ways in which the societal demands for materials often have an adverse effect on environmental quality.

Fourth, there is new concern that the rate at which the earth is being mined will lead to severe shortages for certain key materials in the near future, and that industrial processes for minerals and materials are significant consumers of energy.

Fifth, in addition to these external pressures, there are important forces working within the field itself. There is growing realization that basic concepts and questions pervade throughout various classes of materials. These intellectual stimuli serve to draw together individuals from many different disciplines to achieve, by combining their knowledge and skills, that which none could achieve alone.

Thus, through this combination of external and internal pressures, we see the multidisciplinary field of MSE evolving, forwarding the quest for deeper understanding of materials on the one hand and, on the other, bringing this scientific endeavor closer to the needs of technology and society generally. We are led, therefore, to propose the following definition:

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 uses.

SOME ASPECTS OF MATERIALS SCIENCE AND ENGINEERING

Materials

What is meant by “materials” in MSE is clear to anyone until he is asked to define it. Are foods materials? Fuels? Drugs? Bones and muscle? In the broader sense, the answer is “Yes.”

However, a tradition has built up in MSE which focuses on industrial or engineering materials. Thus food, fuels used in their natural state, and some other categories are usually excluded. Exclusion is often based on lack of modification of the original properties of the material prior to usage; little processing; substantial tolerance of the product to quality variations; or little durability in use. These boundaries have, of course, been changing with time. But for the purposes of this report, the principal classes of materials falling within the field of MSE are broadly covered by the typical labels: ceramics and glass, metals and alloys, plastics, single crystals, and certain natural materials such as wood, stone, and sand.

But new ways of categorizing materials are evolving. Because of the spill-over of knowledge and applications from one class of materials into another, the traditional boundaries between classes of materials are becoming increasingly blurred. Instead, it is becoming common and useful to consider and classify materials according to their function or application—for example, structural, electronic, biomedical, energy, etc.

Disciplines

The principal disciplines and subdisciplines involved in the multidisciplinary field of MSE are solid-state physics and chemistry, polymer physics and chemistry, ceramics, and metallurgy, and portions of most engineering disciplines. The field embraces parts of synthetic, structural, dynamic, and theoretical chemistry; and chemical, mechanical, electrical, electronic, civil, environmental, aeronautical, nuclear, and biomedical engineering. Many other disciplines and subdisciplines, such as economics and management, interface with these central activities. It is to be emphasized that the disciplinary or subdisciplinary boundaries to the field are indistinct and continually evolving.

Activities and Style

MSE. encompasses the entire spectrum of R & D relevant to materials, from basic or curiosity-motivated research done without much thought of its immediate application, to the engineering and design of devices, machines, and structures on the basis of available materials data. It can include such fundamental topics as the structure and properties of solidified gases at very low temperatures or the optimization of materials design for high-temperature gas turbines, the developing of an ability to predict the physical properties of plastics from a knowledge of their molecular configurations, or the exploration for suitable catalysts for treating automobile exhausts. MSE also interacts strongly with related activities: education and teaching, commerce and industrial economics, national security, and environmental quality. The multidisciplinary nature of the field undoubtedly aids its involvement in a wide range of human concerns and interests.

MSE includes both the scientific, rigorous approach to acquiring and applying knowledge and the long-standing empirical method. Often the two go hand-in-hand, building on each other—empirical observations of the behavior of materials suggest phenomenological models for their explanation which, in turn, often get refined into predictive, analytical models. Both the phenomenological and more rigorous approaches suggest new ways to proceed, say, in endeavoring to optimize desired material properties. Examples of this mixture of the scientific method and empiricism are the continuing searches for superconductors with higher transition temperatures, for cheaper and more efficient catalysts, and for textured alloys with superior strength-to-weight ratios.

But always, in its most ambitious reaches, MSE relates a fundamental understanding of the behavior of molecules, atoms, and electrons to the real world of the performance of devices, structures, machines, and products. MSE offers opportunities to combine the deep intellectual challenges and excitement of basic research with the satisfactions of solving real and socially significant problems.

Relevance

Even though the field includes vital activities in basic research not immediately related to applications, MSE as a whole is directly relevant to all man's activities that involve machines, devices, or structures. It is involved with the improvement of communications, computers, consumer goods, national defense, energy supply, health services, housing, transportantion, and so on. Either directly or through the intermediary of these technologies, the field is also very relevant to several other key concerns of mankind, particularly environmental quality and the conservation of natural material and energy resources. In sum, the field plays an essential role in raising mankind's standard of living and in enhancing economic, social, and national security. MSE is, then, a necessary, though by no means sufficient, component for the progress and even survival of mankind. While we cannot always be certain beforehand where MSE will lead us, we do know that without it, technological advance would slow down and society would have to live with, or do without, the present state of technology.

ILLUSTRATIVE EXAMPLES OF MATERIALS SCIENCE AND ENGINEERING

Some Past Achievements

One way of describing MSE is to give some examples of earlier achievements. The listing in Table 3.1 is arranged under three column headings—Basic Research, Material or Process, and Examples of Applications. The table illustrates the interdependence of these three categories; but by no means should it imply that the initiative for a new development always comes from basic research. The opposite is more typically the case. Occasionally, basic research in materials turns up discoveries which may be of momentous importance, such as the discovery of superconductivity, the theory of transistor action, and the discovery of masers and lasers, but more often than not basic research is stimulated by, and supported because of, its ultimate relevance to practical applications as foreseen by the sponsor if not always the actual performer.

In addition to the examples in Table 3.1, a number of past achievements have been chosen for broader study aimed at elucidating the characteristics of MSE and the way it operates. More complete case studies are given in Appendix A of this Chapter, but here we offer some comments on particular features of each example.

TABLE 3.1 Some Achievements in Materials Science and Engineering

	BASIC RESEARCH	MATERIAL OR PROCESS	EXAMPLES OF APPLICATIONS
1.	Elemental semiconductors, effects of impurities on conduction properties, impurity chemistry (segregation, alloy systems), crystal-growth studies, dislocations, surface chemistry, etc.	Zone refining, float-zone crystal growth, controlled doping in Czochralski growth, epitaxial growth, controlled alloying, diffusion, oxide masking, photo- and electron-beam lithography.	Transistor, integrated circuits, tunnel diodes, impatt diodes, charge-coupled devices.
2.	Binary compound semiconductors, plus special emphasis on optical properties—luminescence, electroluminescence. Band structure theory.	Increased control over epitaxial growth—liquid-phase epitaxy. Gallium arsenide, gallium phosphide, silicon carbide. Group II-Group VI compounds.	Light-emitting diodes, injection lasers, bulk negative-resistance devices.
3.	Ternary-compound semiconductors . Phase-diagram explorations. Properties vs. composition.	New semiconductor materials for optical and nonlinear optical applications.	
4.	Ferroelectrics. Dielectric properties of polar and non-polar crystal lattices. Pyroelectric properties.	Nonlinear optical materials Electro-optic materials. (e.g. $LiNb0_3$, $LiTa0_3$, $Ba_xSr_{1-x}Nb0_3$, $Ba_xNa_{1-x}Nb0_3$, etc.) Lead zirconate titanate.	Optical modulators, deflectors, harmonic generators. Parametric oscillators and amplifiers. Infrared pyroelectric detectors. Microphones. Transducers. Piezoelectric filters.
5.	Phase-equilibria studies under extremes of pressure and temperature.	Synthesis of diamond. Boron nitride.	Abrasives
6.	Superconductivity. Electrical magnetic and thermodynamic properties of metals at extremely low temperatures. Many-body theory. Lattice modes.	New superconductors—high transition temperature, high critical current, e.g. ß—tungstens . Superconducting switches. New phenomena—Josephson effect—in thin superconducting films.	Superconducting solenoids, for high magnetic fields. Ultra-low electromagnetic signal detectors. Cryogenic logic.

BASIC RESEARCH		MATERIAL OR PROCESS	EXAMPLES OF APPLICATIONS
7.	Magnetic properties of insulating crystals—relating magnetic properties to crystal structure and composition.	Ferrite crystals. Garnet crystals.	Microwave devices-circulators isolators. Bubble-domain memory and logic devices.
8.	Magnetic alloys—relation of magnetic properties to composition, micros tructure, and deformation process.	Grain-oriented silicon-iron . Permalloy. Remendur. Cobalt rare-earth alloys.	Transformer cores. Nonlinear magnetic devices-pulse transformers, amplifiers, memories, Controlled coercive-force alloys. High coercive-force alloys.
9.	Physical chemistry of hydrothermal growth process.	Synthetic quartz.	Frequency standards and filters.
10.	Theory of sintering. Basic annealing studies.	Powder metallurgy. Lucalox-high-density, transparent ceramics.	Lamp envelopes. Light-weight armor.
11.	Magnetic properties of polycrystalline ferrites.	Hard and soft magnetic ferrites.	Computer core memories (soft). Magnetic door latches (hard). Deflection cores for TV tubes. High-voltage transformer cores.
12.	Electron-beam optics.	Scanning and transmission electron microscope. Electron beam lithography.	Materials characterization. Integrated circuit technology.
13.	Wetability of surfaces.	Float-glass process.	Cheaper plate glass.
14.	Surface chemistry. Oxidation-reduction reactions. Electro-chemistry—electrode kinetics.	Fuel cells.	Power supplies. Hydrogen-oxygen fuel cells.
15.	Rheology. Physical chemistry of surfaces. Synthesis of compounds.	Structural adhesives. Pressure-sensitive adhesives. Anerobic adhesives.	Joining techniques. Scotch tape, Band-aids, Epoxy cements.
16.	Solidification studies.	Metal fiber spinning, cheocasting.	Steel wire. Aluminum die castings.

BASIC RESEARCH		MATERIAL OR PROCESS	EXAMPLES OF APPLICATIONS
16a.	Solidification studies, transparent analogues.	Directional solidification, better continuous casting. Amorphous materials.	Turbine blades, Magnetoresistance devices, Anisotropic magnets. Premium castings.
17.	High-temperature phase equilibria.	Chemistry of steelmaking. Basic oxygen process.	Cheaper steelmaking. Longer—life furnace linings.
17a	Nonstoichiometry and phase equilibria.	Composition control in crystals.	Improved light-emitting diodes—GaP.
18.	Radiation damage in crystals.	Ion implantation.	Integrated-circuit technology .
18a.	Radiation damage in polymers.	Polymer cross-linking.	Heat-shrinkable polyethylene and polyvinylchloride.
19.	Thermal expansion of ceramics. Nucleation and phase precipitation.	Pyroceramics.	Ovenware.
20.	Nucleation theory.	Ductile iron.	Engine blocks.
21.	Thermodynamics of phase diagrams, chemical processes. Particle strengthening.	Dispersion alloys—internally oxidized particles to strengthen materials; thoria-dispersed nickel; dispersion-hardened A1, Cu, Ag. Spinodal decomposition.	Aerospace alloys. Aluminum conductor cables. Copper conductors, electrical contacts. High-strength and magnetic alloys.
22.	Structural stability in high-radiation flux.	Fuel elements. Stable cladding.	Nuclear power.
23.	Fracture studies. Fatigue; dislocation theory,	Nondestructive-testing techniques. Computer-aided metals design. High fracture-toughness materials.	Wide range of structure high-performance applications.
24.	Deformation theory for polycrystalline solids. Annealing behavior. Precipitation hardening. Recrystallization. Super plasticity.	Hydrostatic extrusion and forming. Textured materials. Superplastic forming. Tableware. Shape and memory effect.	Shapes and parts. Transformer steel. Alnico magnet. Spring metals. Heat-shrinkable metals.

BASIC RESEARCH	MATERIAL OR PROCESS	EXAMPLES OF APPLICATIONS
25. As above.	New alloys. Al-based and Ni-based precipitation hardening. Precipitation hardened stainless steel.	Aerospace applications. Turbine blades. Razor blades. Quality cutlery.
26. Spectroscopy of impurities in crystalline hosts.	Optically pumped lasers.	Optical communications. Ranging for ordnance and surveying. Machining.
27. High-temperature erosion studies. Pyrolysis.	Firebricks. Weather resistance. Ablation. Carbon-fiber processing from polymer precursor.	Reinforced plastic nosecones and ablation shields. Furnace linings. Constructional materials.
28. Spectroscopy of impurities in glasses.	Photochromic glasses.	Sunglasses. Windshields.
29. Ion exchange and diffusion in glasses.	Surface-strengthened glass.	Strong fibers. Optical fibers.
30. Photochromic effects in crystals. Optical radiation damage.	Holography.	Optical memories.
31. Crystal growth.	Vapor-liquid-solid growth processes.	Cold cathodes.
32. Heterogeneous catalysis.	Electroless deposition.	Electroless coatings of Au, Co, Cu, Ni, Sn, Al, Mg, Ti.
33. Orientation of macromolecular chains.	Spinning of fibers from melts and solutions: rayon, nylon, acrylins, polyesters.	Synthetic textiles.
34. Role of molecular networks in determining the properties of rubber.	Vulcanization.	Tires.

Heatshield Design Problems

(See Appendix 3A; p. 3–60)

This example particularly illustrates the systems approach. The materials development is embedded in a broader design problem, but the overall design is strongly influenced, in fact almost completely determined, by materials capabilities. The development of an adequate heatshield for manned re-entry of space vehicles required the contribution of a wide range of disciplines and utilized contributions from several organizations and many locations. In our language, this program is science-intensive. The program had a clearly defined overall objective and is an example of responsive materials R & D.

Transistors

(See Appendix 3B; p. 3–67)

The transistor story emphasizes the changing nature of a materials R & D program with time. In its early phases, only fundamental understanding of the nature of electrical conduction in semiconductors was involved. The motivation or "application" was stated only in a most general way, but there was a perceived need to replace vacuum tubes in communications circuitry. Although this program substantially increased understanding of the solid state, it necessarily built on much basic work in physics and chemistry which had been completed in earlier decades. As the program succeeded in providing device capabilities, the emphasis naturally shifted from research on phenomena to the engineering aspects of design and manufacture. Movement of personnel from research to development played an important role. This program provides a particularly strong example of close coupling between basic research and engineering. The solid-state industry which has grown out of the original transistor work is the arch-type of a science-intensive industry and creative materials R & D. The transistor story also illustrates the cardinal importance of proper intellectual and working environment for innovative materials R & D. A sense of direction was provided by the management in a sufficiently general way so that individual creativity and insight were encouraged, and yet was sufficiently definite to arouse the enthusiasm and dedication of the experts involved. Leadership in the research and development programs fell naturally on those able to span intellectually and motivationally the full scope of such programs.

Razor Blades

(See Appendix 3C; p. 3–72)

In an industry which might be thought of as experience-based, the internal objective to achieve substantial improvement in shaving performance led to a materials R & D program requiring considerable science and sophisticated techniques. The program was quite interdisciplinary, involving experts in biophysics, physical chemistry, physical metallurgy, and contributions from the life sciences. The use of a new scientific diagnostic instrument, the scanning electron microscope, for the first time provided a way of measuring the performance difference of various razor-blade materials. A key point in the program was the somewhat accidental observation of deposition of thin films of polymers on steel surfaces. The major feature, however, was the organizational climate and the ability of the investigators to recognize the importance of this observation and to properly exploit it for their overall objective. Materials R & D seldom runs a neatly planned course; it requires perception, training, and freedom to capitalize on an unexpected event or observation. The result was a new, hard-alloy coating of the blade covered, in turn, by a thin, tough plastic layer.

Synthetic Fibers

(See Appendix 3D; p. 3–74)

The field of synthetic fibers, spanning several decades in time, is very large in terms of the number of investigators and organizations involved in R & D as well as in terms of market volume. As in the case of the transistor, the early effort was on basic understanding, but there was also a perceived need to improve on natural fibers. In time, engineering emphasis was added but not at the expense of further scientific investigation so that we now find the general problem of synthetic fibers being attacked across the entire spectrum from basic science to engineering. The major contributions to this important development have been made by chemistry, but inputs were required from other disciplines such as the metallurgical development appropriate containers for the hot-liquid corrosive melt. To reach the ultimate customer, this materials advance also required innovations in spinning and weaving machinery for the new fibers.

Textured Materials

(See Appendix 3E; p. 3–79)

Textured materials is a description used in this report to refer to polycrystalline microstructures in which a degree of control is exercised on the alignment of neighboring crystals. Examples are permanent magnet alloys, and high-strength phosphor bronze alloys for use as springs in relays and connectors.

The cental theme of materials science in the relation between composition, structure, and properties is beautifully illustrated by this program. Here the emphasis is on structure, more particularly control of structure, and its influence on properties. Basic work by a physicist, followed many years later by metallurgists in the laboratory and supported by extensive computation techniques from the mathematicians, has led to a capability for predicting the structure and related physical properties of materials in terms of the processing steps used in its preparation. This program has set a high standard for the direct contributions which science can make to practical programs.

Integrated Circuits

(See Appendix 3F; p. 3–81)

Although this is a logical follow-on to the transistor story, it is included as a separate piece because different aspects of materials R & D are illustrated. In the rapid development of integrated circuits, effective coupling has been achieved principally through cross-licensing of patents, among industrial organizations which are highly competitive. Whereas the transistor required important new scientific understanding, the creation of the sophisticated integrated circuits resulted principally from inventiveness and engineering ingenuity, particularly in processing technology. At the same time, the small dimensions and extreme material purity needed for integrated circuits could not be achieved without a wide array of diagnostic tools and instrumentation provided by earlier unrelated scientific programs.

Aluminum Conductors

(See Appendix 3G; p. 3–86)

Copper conductors for electricity come from an experience-based industry, but recent problems in copper availability as reflected in price have injected new science and engineering into the industry. Although aluminum as it existed a few years ago was unsatisfactory for many copper-wire applications, materials R & D has demonstrated that it is possible to modify and control aluminum alloys to meet the necessary properties, such as electrical conductivity, ductility, and corrosion resistance. The objectives of the program were clear, the time scale was relatively short, and the contributions were more of an engineering nature than scientific. This is a clear example of the user in a sciences-intensive industry demanding new material capabilities and providing leadership to attain that end. It illustrates the ability to develop, through materials R & D, a substitute material to satisfy a specified function.

Polymer-Modified Concrete

(See Appendix 3H; p. 3–88)

Concrete and cement is an experience-based industry with long traditions, very high volume, and intense pressure on unit cost. An expansion of the polymer field has now touched this long-standing material and is providing new capabilities through polymer latex-modified Portland cement. At the same time, new understanding is being generated concerning the fundamental mechanisms of cementitious attachment. Closer coupling has been accomplished between academic and industrial investigators in this area.

TV Phosphors

(See Appendix 3I; p. 3–91)

The discovery of an important red phosphor illustrates the wide span of scientific knowledge which is sometimes required in materials R & D and the very close linkage which can be obtained between new scientific understanding and very practical application. Scientific studies in support of laser host materials led to the discovery of a commercially significant red phosphor. A central element of this program was the ability of the investigators to pursue and exploit unpredicted observations.

Ceramic Oxides

(See Appendix 3J; p. 3–96)

Major new materials may result from the application of new understanding in one field applied to a different class of problems. Such was the case in the development of new high-density and, therefore, pore-free ceramics. Insight and stimulation for this work resulted from the earlier contributions of metallurgy and physics.

Problems and Failures

The conclusion should not be drawn that all programs in materials R & D are successful. Large-scale programs where criticism is most likely to strike are usually embedded in such complex situations that it becomes very difficult, after the fact, to identify the circumstances which blocked success. In some cases, substantial materials development is done in support of a given application; cancellation of the application then calls the materials development into question. A well-known example of this sequence was the major investment in titanium in the 1950's which had been criticized by some as being unjustified or overly expensive. The titanium development program was conceived and conducted in direct response to projected needs of the Air Force for supersonic aircraft which could not be built with the then-existing materials. By the time a substantial titanium industry had been established in this country, the successful development of intercontinental ballistic missiles superseded the Air Force plans for constructing a new supersonic fleet of aircraft. The titanium development was left without its largest potential customer. The titanium program itself, nevertheless, appears to have been successful in evolving a new engineering material together with the necessary processing techniques to meet stated performance requirements.

Examples of more recent attention in the materials community, such as Corfam or the Rolls-Royce composite carbon-fiber-reinforced compressor blade, are equally complex to the extent that it is not clear whether the materials R & D was or was not adequate.

A famous and tragic example of material failure was the metal fatigue experienced in the early commercial jet aircraft. The aluminum alloy used in the fuselage had been analyzed and tested in many ways, but apparently insufficient attention had been given to the precise design details in the ultimate aircraft structure, particularly the influence of the window cutouts on crack propagation under the alternate loading and unloading caused by a hunting pressure system.

A similar type of failure was experienced in the selection of a stainless steel for a high-pressure bottle in a space application. An alloy was chosen on the basis of its high modulus, but its strength suffered from the welding process. A better and stronger overall product could have been obtained by the choice of a stainless steel with less strength but superior welding characteristics.

Engineers were surprised when they developed nickel-brass alloy springs for telephone switching equipment. Although these components had received exhaustive environmental testing before they were released to production, the springs installed with new equipment in Los Angeles began to fail after a relatively short time in service. Careful “technical detective” work showed that stress-corrosion cracking occurred in the presence of airborne ammonium nitrate in periods of high humidity.

Trouble has been experienced in the space program with solder joints on printed circuit boards. Experience has now shown that cycling between the extreme temperatures in service can cause failure of the solder and loss of electrical continuity.

Tinted glasses which are used for absorption of solar radiation have cracked because the stresses created by uneven solar absorption—for example, at a shadow line—have exceeded the tensile strength of the glass.

Polyacetyl plastics have desirable properties, but failures in service have brought out the fact that in the presence of oxides of nitrogen a chemical reaction is catalyzed which completely degrades the material.

In the consumer area, there have been a number of materials developments which have been less than successful. Plastic components of some appliances, particularly refrigerators and vacuum cleaners have lacked adequate durability. In refrigerators, plastic parts such as doors, shelves, chiller trays, and the like have failed in service. In vacuum cleaners, the floor or rug nozzles sometimes break when the tools are made of plastic. The sealed-rod type of heating element used in most cooking appliances does not always stay sealed. The filler material which is supposed to prevent contact between the heating wire and the outer cover has proved to be hygroscopic, and when the seal fails an electrical leakage path to the outside of the element creates a shock hazard. A more complete analysis of the complex requirements imposed on this filler material in service might have corrected this problem during development.

Finally, there are the failures of omission. The public or the customer often does not know what to ask for because they are unaware of what materials technology may be able to provide. This is in an area in which the materials community might provide more leadership.

Project SAPPHO[1] in Great Britain has addressed the question of success or failure in industrial innovation in the chemical and scientific instrument industries. Although Project SAPPHO is more general in scope than materials

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[1] A Study of Success and Failure in Innovation; carried out at the Science Policy Research Unit, University of Sussex.

R & D, it seems likely that some of its conclusions are applicable to our interests. One principal conclusion is that the successful innovators have a much better understanding of user needs. In our consideration of materials R & D, this means that the materials developer should establish a thorough understanding of the way in which his materials are to be applied. Too often, inadequacies in materials R & D appear to result from insufficient knowledge of the entire system in which the materials work is embedded.

Another significant conclusion of the SAPPHO study is that success is not so much correlated with institutional size as with the size of the group that worked on the project.

CHARACTERISTICS OF MATERIALS SCIENCE AND ENGINEERING

General

MSE is an arena in which traditional scientific disciplines interact, as appropriate, with engineering disciplines. These interactions are enhanced by common interests in achieving particular technological goals. And increasingly, these technological goals are being selected from the point of view of overall societal value. Thus, from an overall perspective, MSE has the following prime characteristics: (a) It is a multidisciplinary field embracing an enormous diversity of disciplinary and interdisciplinary activities and programs, and (b) it is science in action to meet man's needs even though, at any given time, a number of the activities in the field will be more curiosity-motivated than application-oriented.

This multidisciplinary field embraces activities in the traditional single disciplines, including the work of individuals, as well as interdisciplinary activities which, by definition, require the collaboration of two or more individuals. COSMAT believes that the need for interdisciplinary projects and programs can only grow in the future if many of the technological problems facing society are to be met.

There are two main modes for MSE: it is responsive to specific needs, and it is creative.

Viewed as a whole, MSE is science and engineering aimed at satisfying specific needs. In the responsive mode, these needs supply motivations and establish a climate for close interaction between the materials specialists and the design engineers. This, in turn, facilitates feedback of changed requirements to the materials specialist as his work becomes steadily more refined. The formulation of new materials for medical implants has involved close interplay between clinical experience and material characterization. The development of continuous hot-strip rolling of sheet steel was motivated by the need for lower-cost manufacturing processes. Fundamental studies on electrode reactions allowed the discovery of an anodic-protection process which makes it possible to employ carbon steels or stainless steels in handling corrosive media such as hot sulfuric acid.

MSE is also creative. This field of endeavor has its share of individuals with gifted foresight and insight. Knowledge of new advances in scientific understanding, coupled in one individual's mind with knowledge of potential applications, occasionally leads to the evolution of a material with new properties which is then recognized to have wide application utility. The early work of Bain and Davenport on the decomposition of austenite led directly to the concept of the hardenability of steel. In another example, Boesch and Slaney were familiar with the original work of Pauling relating the bond between atoms of sigma-forming elements to the average number of electron vacancies in the bonding orbitals of certain elements. They also knew of a formula which Rideout and Beck had derived from this relationship to predict the composition of sigma-forming alloys in certain ternary systems. Starting with this scientific knowledge, Boesch and Slaney were able to produce nickel-based superalloys without the sigma phase and therefore not subject to the entrée of time-temperature induced brittleness.

Yet another illustration is the detailed understanding of the exchange-coupling in magnetic systems and the critical influence of minor impurities which has led to the development of superior garnets for utilization as isolators in electronic circuits.

Nature of Materials Research

Our definition of MSE includes both the generation and the application of knowledge about materials. Materials science is usually concerned with the generation part, materials engineering with the application part.

Two of the vital ingredients for viable, healthy MSE are the ever-present needs and areas of application on the one hand, and the generation of new materials and knowledge concerning materials on the other. Continuing societal needs and desires will always provide areas of application for new materials developments. But the flow of new materials developments would dry up if basic, nonprogrammatic research in the field of MSE were to be suddenly removed. There might be no noticeable effect on the rate of introduction of new technology for several years, but thereafter, the technological capability of the U.S. relative to other countries would decline steadily. The decline would be precipitous in some (not all) of the fast-developing high-technology sectors, slower in the low-technology sections. But since the typical time-span between the performance of basic research in materials and its eventual usefulness to society is 10 to 20 years, the U.S. could be led to a seriously inferior position on this time scale. Such a delay-time for the fruits of basic research seems to be intolerable for many industrial managements, politicians, and even for the general public, but it is relatively short compared with the waiting period for the fruits of research in other fields such as astrophysics and elementary-particle physics.

Consider a scale which extends from the more basic research on properties of certain materials to the routine application of these materials. At the left-hand of the scale are the investigations aimed at understanding and describing the observed materials phenomena. Such programs are typically motivated by the curiosity of the investigator, his creative insight, and by unanswered questions in the field itself. This approach to research has provided an incredible and invaluable foundation throughout the field of MSE. It is the basis for better understanding of the properties of many engineering materials and for the more systematic and efficient solutions of materials problems. Not only is basic research the key to improvement across the whole field, but it is most often the source of dramatic innovations in the field. The laser could never have been developed by applied-science or engineering improvements to incandescent or fluorescent light sources. Basic research may be closely coupled to engineering and development as was true in the early days of the transistor, or it may be very loosely coupled as is the case in some surface research where a considerable buildup of knowledge is required before practical problems in catalysis or surface deterioration can be treated in a systematic way.

At the right-hand end of the aforementioned scale is routine application of engineering materials; for example, those well described in the handbooks and those with a long history of usage. It is also important to recognize that there remain many practical materials problems which will be most efficiently resolved by empirical approaches based on existing knowledge and past experience, It would be a disservice to denigrate this type of activity or to imply that it will no longer make an important contribution to society. Good engineering has the responsibility to reach objectives in a cost-effective way.

Between these two extremes on the scale is a continuum where science blends into engineering and there is often strong coupling between the two. Figure 3.1 is a simple representation of the change which is taking place on the science-engineering dimension with time. The pertinence of this simple diagram is not always apparent because a scientist may from time to time become interested in an application and may, himself, move into engineering. Similarly, an engineer may find that the most direct route to his application is, first, the acquisition of new scientific knowledge or understanding, and so he may sometimes perform as a scientist. Although this blending may be somewhat distracting to one who is seeking a simple picture of MSE, it is in fact one of the very important ways in which coupling is effected between science and engineering in the field. In general, such interaction is very efficiently carried by personnel moving from one area to another, within the same organization. The most valuable individuals in a R & D organization are usually those who can straddle, both intellectually and in practice, the interface between science and engineering,

The time scale (program duration) often has a strong influence on the science-engineering dimension. For the most part, very short-term applications are handled by engineering methods, for there is not time available to acquire additional scientific insight; however, exceptions may occur if the applications are exploiting recent discoveries. The early days of the transistor and the laser were examples where close interplay between science and engineering was achieved even though the time for development was short. Well organized materials-development programs with longer than a few years' duration may start with an emphasis on scientific understanding. As such long-term programs progress, the emphasis tends to shift to engineering, and in the final phase, further scientific research may be only very loosely coupled to the engineering work.

In addition to the above operational forces which are serving to shape the role of materials research, there are also significant internal, intellectual forces. It is now recognized that interests in basic phenomena and

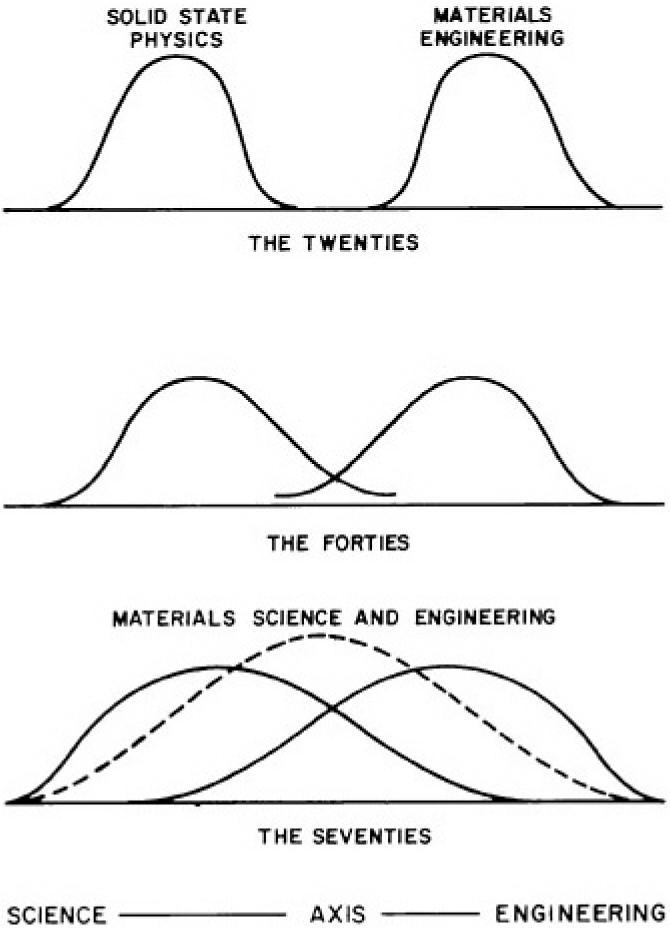

FIGURE 3.1 CHANGE WITH TIME OF COUPLING BETWEEN SCIENCE AND ENGINEERING IN THE MATERIALS FIELD.

materials properties transcend the traditional classifications of materials, such as metals, ceramics, plastics, etc. The unifying theme throughout MSE, which brings together a broad span of activities and a multitude of materials, is the relation between the working properties of a material, or the phenomena that it can exhibit, and its structure and composition—the so-called structure-property-function relationship. The properties are diverse (e.g. structural, mechanical, electrical, magnetic, optical, chemical, biological, etc.) and the material types are many, but increasingly those engaged in materials research are acquiring the ability to maneuver in these many dimensions in whatever way seems most effective for achieving the desired scientific or technological goal.

Nature of Materials Development, Design, and Engineering

Society wants things or services which require materials, but there must be the intermediary of a design or application specialist to transform material into a product or service.

Design is used here in the broadest sense of "the process of selecting the means and contriving the elements, steps, and procedures for producing what will adequately satisfy some need,"[2] or in an engineering context, "the drawing up of specifications as to structure, forms, positions, materials, texture, accessories, decorations in the form of a layout for setting up, building, or fabrication,"[3] The design engineer has broad responsibilities for understanding the nature of the materials utilized. In addition, he has responsibility for quality control and product evaluation.

The contribution of materials development to the public consumer is almost inevitably made through a design or application. There are exceptions such as synthetic sapphire which is marketed directly as a material, but these are comparatively rare. Much of the work in the materials development is naturally supportive or responsive in that new and demanding designs are frequently limited by available materials or material properties. As a case in point, the designer of a turbine blade for a jet engine would like a very high temperature of operation for thermodynamic efficiency. The lack of a high-temperature, high-strength material for this service was met by the materials community through the development of special alloys with controlled microstructure. The search for higher-intensity, more-efficient lighting was supported by the development of pore-free aluminum oxide which is highly translucent and yet can contain the high-pressure sodium discharge. In the creative mode, materials development often is the key to entirely new designs. Such new capabilities pervade all technology, but two familiar examples will illustrate the point. The one-piece molded fiberglass sailboat which is leak tight and requires little maintenance is a direct consequence of the development of fiberglass. Pyroceram cooking-ware resulted from a

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[2] Webster's Third New International Dictionary, 1966.

[3] Ibid.

program to develop high-performance ceramics for missile nose cones.

In either mode, whether responsive or creative, the materials development must work through a designer or applications engineer to reach the consumer and connect its contribution to society. Therefore, the interface between the materials developer and the designer is of paramount importance. A methodology or philosophy which has been successful in smoothing this interface is the systems approach. The interdependence of the designer and materials developer is so strong that it is frequently impossible to apportion credit or blame when a program has succeeded or failed. Thus, the materials development specialist has a responsibility to establish close liaison with the design or applications engineer.

A considerable portion of the COSMAT inquiry has been devoted to the relationship between materials development and national goals. In some programs, materials development does play an important and even central role, but only in conjunction with other factors. Examples of both past and possible future programs stress the design or application aspect even though we are primarily concerned with the materials problems. The reason for this is that the device or product is the common ground for understanding between the materials community and the general public. We recognize that attention to materials problems alone will not normally solve any of the concerns faced by society, nor will exclusive attention to design without adequate materials development. Therefore, this report emphasizes the inseparable connection between materials development, design, and application.

Systems Approach to Materials Development

Methods of systems planning and systems engineering, in which the repercussions throughout the system of a change introduced at any point in the system are recognized and taken into account have been highly developed, for example, in defense and communications systems. The systems approach is sometimes shrugged off as “just trying to think of everything,” but this is essentially what it is. There are various needs and opportunities for extending this approach in the materials field.

Technological Systems of Materials

As a technology advances, each material tends to become more highly adapted to its specific role in the end-product. These products are composed of systems of materials, each chosen to fit a particular profile of functional properties and environmental requirements. Modern technological products—nuclear reactors, jet engines, integrated circuits, etc. —consist of intricate, highly interdependent assemblies of materials, each carefully adapted to its specific role in the total structure. Changes made in any one part of the system can have a very significant effect on the performance of the whole system (for example, the materials problem that Rolls-Royce faced when it introduced carbon-fiber-reinforced composites for compressor blades) and can often necessitate complete redesigns.

Materials Cycle

The materials cycle is also a system in which steps taken at any part of the cycle can have repercussions (often surprising ones) at other parts of the cycle as well as having concomitant effects on energy supplies and the environment. For example, a successful demonstration of a magnetically levitated transport system could lead to a dramatic increase in demand for liquid helium and/or rare earths useful in magnetic alloys. The successful demonstration of power generation by thermonuclear fusion or direct conversion of solar energy could cause great changes in the demand and consumption patterns for fossil fuels. In a different dimension, environmental legislation may reduce use of certain materials currently in high demand (e.g. mercury in paper processing and batteries), accelerate use of others (e.g. platinum for automobile emission catalysts), and offer increased availability of some (e.g. sulfur from stack recovery). One of the most important emerging forces in the materials cycle is the limited availability of certain raw materials. These growing shortages on various time-scales have important repercussions throughout the cycle, but particularly spotlight a vital role for MSE—to develop substitute materials made from abundant or renewable natural resources and to engineer ways of making do with considerably less of the scarce materials. Thus, the need for concerted approaches wherever possible rather than just haphazard or separate approaches in the materials cycle is becoming more critical.

Methodology

The phrase “systems approach” describes a methodology which has been developed to deal with complex systems constructed of many closely interacting parts. The systems approach provides an effective framework for a program in which many different groups or individuals must make specialized contributions. It is particularly effective in highlighting those critical parts of the program which require particular attention and extra effort. The systems approach has been utilized to deal with a wide variety of problems in technology, business, politics, and national security.

In MSE, the systems approach is needed to provide the best match between the materials development and its ultimate application. Rather than start immediately upon a materials development, the MSE practitioner must first ask how the material is to be employed and for what purposes. This is not a casual question but rather a deep and searching one. The actual function required of the material must be delineated, together with an understanding of the technical and economic tradeoffs between materials properties, processing methods, and performance difficulties. This prior understanding of the many factors at play can also lend to the possibility of alternate solutions, so that the result may be creative as well as responsive. During the life of the program, new information will become available as to the practicalities of achieving certain materials properties. This information can be fed back in a meaningful way to the applications designer so that the overall engineering solution can be modified. A flow sheet of the overall process is illustrated in Figure 3.2.

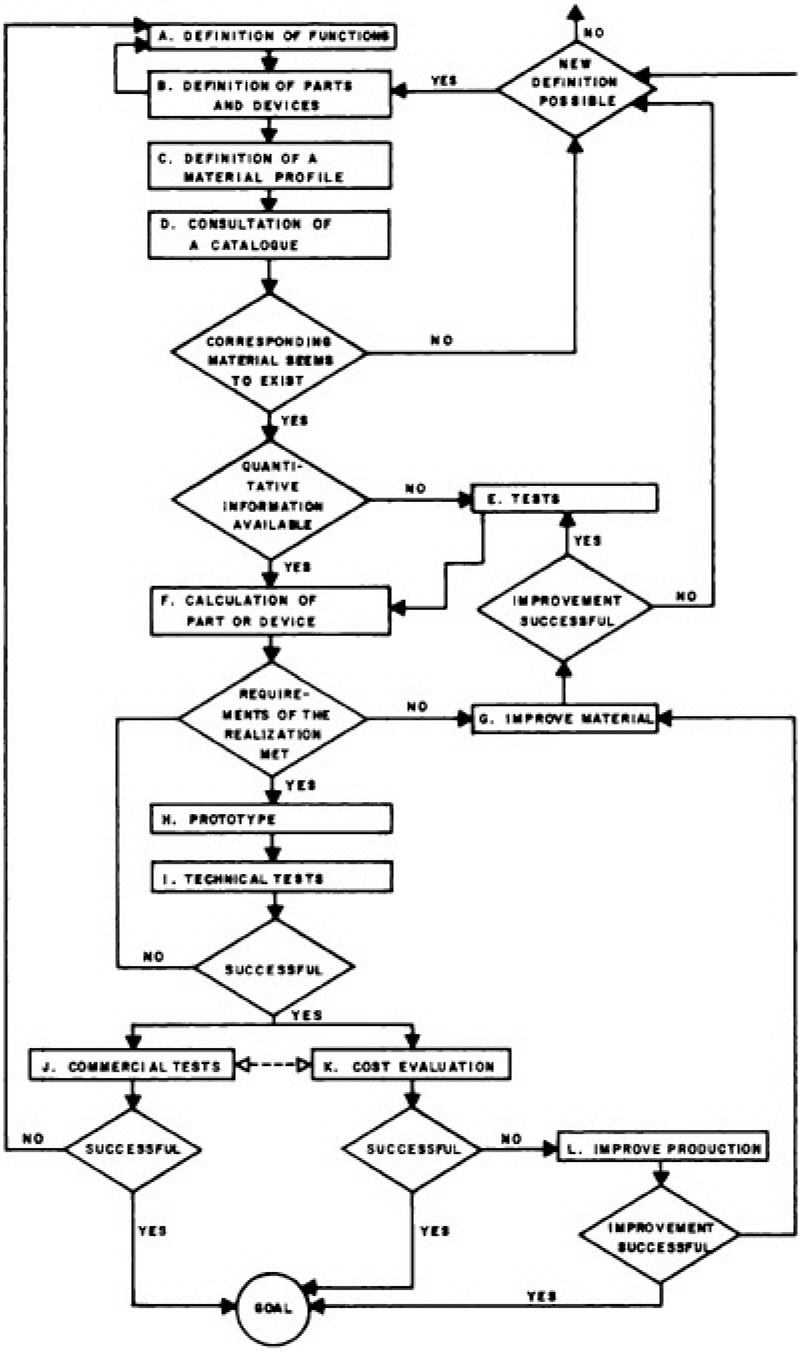

FIGURE 3.2 EXAMPLE OF SYSTEMS ENGINEERING APPLIED TO MSE TAKEN FROM OECD REPORT ON “PROBLEMS AND PROSPECTS OF FUNDAMENTAL RESEARCH IN SELECTED SCIENTIFIC FIELDS—MATERIALS.”

Contemporary Expansions of the Systems Approach

While the systems engineering helps MSE make its contribution to society more effective, it also seems to be the area where there has been the most difficulty. When we reviewed a number of projects in which MSE failed to live up to expectations, we most frequently found that some aspect of the systems approach was missing.

It is noteworthy that, in the past, most contributions in MSE have neglected one key element of the total system, namely, the environmental impact. In selecting or developing materials for a particular application, the material cycle must be kept in mind. To move towards the contemporary national goal of environmental quality, materials recycling and disposal must be an important element in materials decisions. With the striking control over materials properties which MSE can provide, there are many tradeoffs which can be considered between raw-material costs, fabrication, product performance, and ease of recycling or disposal. The latter two have assumed increasing relevance and must be fully accounted for in future systems considerations by MSE practitioners.

Another growing force in the materials cycle is the supply/demand pattern for energy. This impinges not only on the energy consumption entailed by a new product in its manufacture or service but on all stages of the materials cycle. No major development at one part of the materials cycle can be dealt with in isolation; the consequent impact on energy resources and distribution at other stages of the materials cycle must also be considered.

In summary, there will be growing need in the future to pursue the systems approach both internally and externally in major MSE programs. The complexity of modern technological hardware requires the systems approach on internal materials systems; the mounting problems of resource availability, fuel supplies, and environmental quality require the systems approach to be applied to MSE engineering in an external context as well.

Multidisciplinary and Interdisciplinary Activities

We have already noted that the field of MSE is multidisciplinary in that it embraces activities in a wide range of the traditional disciplinary areas, activities which are very often undertaken by individuals. But while much basic research and creative invention may be carried out in the disciplinary mode, within the multidiscipline of MSE there are growing opportunities for various interdisciplinary endeavors in which a variety of specialists, many of whom are also in the forefront of their respective disciplines, interact in achieving progress towards scientific or technological objectives. Without such interaction many well-known achievements, such as the transistor, color phosphors for TV, reactor fuel elements, and titanium aircraft skins would not have been possible.

Even in basic research, with new knowledge as the prime objective, there is increasing awareness of the fact that very often significant progress cannot be made within one discipline alone. It is frequently necessary, instead, for individuals from two or more disciplines to combine their skills, their knowledge and approaches to attain something which none of them could achieve on his own. The bodies of knowledge needed for progress in the materials field are often not congruent with the traditional scientific disciplines. They call more-and-more for creative cooperation among disciplines—including the physical and life sciences, engineering, and the social sciences—in order to carry ideas, discoveries, or inventions through to successful application. Interaction, even friction, among specialists from different disciplines is a prime source for the vitality of MSE.

Interdisciplinarity is a practice. Interdisciplinarity cannot readily be measured or quantified; it is an attitude, a way of working, but its mastery is not a self-contained goal as it is in many disciplines. It is an intellectual and adventurous path and those who travel it sense an experience which may have lessons for other spheres of human endeavor. Interdisciplinarity, related mainly to research and development, is a new stage in the evolution of scientific knowledge but it is not necessarily the only way by which science and engineering can advance. Historically, as science broadened, it fragmented into separate disciplines; now interdisciplinarity based on close cooperation brings new combinations together. These interdisciplinary combinations may also be transient, fragmenting in turn, and so the social organization of technology evolves and adapts to changing interests, needs, and priorities, and sometimes coalesces into new disciplines. Much of the strength of MSE lies in its flexibility and adaptability which arise from the diversity of talents, viewpoints, and knowledge bases.

Interdisciplinarity does not imply any submergence of an individual’s personal satisfactions and professional recognition; rather, these may well be enhanced by making his contributions more evident and more widely known. Unlike group efforts in some other fields, MSE projects have the advantage of offering many such opportunities for personal satisfactions within group endeavors. The synergistic interaction and mutual recognition of the value of each individual’s contributions can well lead to achievements and an esprit de corps which surpass those which any person could reach himself.

We see MSE as becoming increasingly more adaptable to interdisciplinary clusters. At first thought, this would seem to conflict with the role of outstanding individuals such as Kroll in the making of ductile titanium; Matthias in the creation of many new superconductors; Land in the conception of the synthetic light polarizer; and Baekeland in the invention of Bakelite plastic. Closer examination shows that the creative efforts of these individuals were followed by interdisciplinary team activities in order to bring their inventions to practical fruition. This pattern will continue. We will always need creative individuals, but in the future they will more likely flourish in a multidisciplinary environment, and they will require the efforts of complementary disciplines in the interdisciplinary modes to complete the innovation.

COUPLING WITHIN THE FIELD OF MATERIALS SCIENCE AND ENGINEERING

As noted, the technological needs of society are generally not congruent with the traditional scientific and engineering disciplines. Nor can they usually be met by engineering alone, but require a balanced range of activities extending from basic research to marketing. Further, there is frequently good reason for coupling the activities of different institutions, academic, governmental, and industrial, in order to achieve technological advances. In this section, some aspects of coupling between disciplines, between activities, and between institutions will be examined together with factors that influence the effectiveness of such arrangements with MSE.

Coupling, as we usually regard it, applies to mechanisms for promoting cooperation, collaboration, and knowledge transfer among individuals, among different parts of an organization, and among institutions. In trying to arrive at a description of this multiply-connected system, it is helpful to note some important dimensions of MSE:

(a) The time scale for a program may vary from a few months to years.
(b) Geographic coupling may be as close as the same laboratory or cooperation may extend over continents.
(c) The size of the project may involve one investigator or many.
(d) One project may find extremely tight coupling between science and engineering necessary, while another may involve only one or the other. Some developments in MSE have required contributions from many disciplines; others have been pursued within just one of the classical disciplines,
(e) In some programs involving several people, the coupling has occurred on a person-to-person basis; in other cases, the coordination is effected through organizations so the individual investigator need not be personally involved in the transfer of his specialized knowledge and findings to other disciplines.
(f) The material of concern may be as simple as a nearly perfect single crystal of one element, or it may be as complex as a composite containing many elements, phases, and impurities.

Loosely-Coupled Multidisciplinary Activities, Tightly-Coupled Interdisciplinary Activities

MSE is a multidisciplinary (MD) field within which there are increasing opportunities for interdisciplinary (ID) programs and projects. Generally we picture the MD activities as “loosely coupled,” whereas the ID activities are more “tightly coupled.”

In the loosely-coupled, MD mode, organizations may be guided by an overall purpose or theme (see below) which serves as a natural stimulus, a common interest, for bringing about collaboration between professionals in different disciplines (D) in a more or less spontaneous way. But it is by no means necessary, or even desirable, for every individual to work in collaboration with others. Some will do so much of the time, others only part of the time, and yet others not at all, each according to their interests and effectiveness. However, the contributions of all are important to the overall purpose of the organization.

An individual working on his own is generating knowledge which others will want to draw on, but he himself may do nothing beyond using the traditional vehicles of talks and publications to see that his knowledge is made available to others. To see that this knowledge gets effectively coupled into other projects is then much more the responsibility of the management or sponsors who are presumably aware of what everyone in the organization is doing and why it is being supported. So in this framework, an individual's mode of operation may very from time to time between D and ID, as he sees fit. In the larger context, the MD mode preserves many more of the traditional academic freedoms for the individual than does the ID mode. It is particularly suited to the longer-term R & D programs (5 to 15 years or more) and is likely to be more acceptable, say, to the academic solid-state science communities than is the ID mode. But the MD mode is probably also a good description of the inclinations of academic metallurgists and ceramists; for example, the metallurgist studying the principles of spinodal decomposition is probably no more tightly coupled into an overall purpose than the solid-state physicist who is developing a fundamental understanding of the nonlinear optics of a crystal. Both will spend most of their time pursuing their own ideas and researches, but both may eventually recognize the practical implications of their work and sense when it is likely to be useful to establish contact, and perhaps even short-term collaboration, with professionals who are more application-oriented. To help further illustrate the nature of the MD mode—essentially all of solid-state physics is vital for MSE, but by no means does this imply that all solid-state physicists are tightly coupled into MSE all the time.

The more tightly-coupled ID mode of collaboration may involve a group of professionals, drawn together from various disciplines to tackle a specific mission or reach a stated goal. It implies a commitment on the part of the individual to choose his own direction and the corresponding time scale in support of the ID group objective. The freedom of the individual has to take second place to the overriding importance of reaching the group's overall objective on time. The individual is constrained to spend a major part, if not all, of his time working on the group project. Obviously, this ID mode is more acceptable to those persons who find satisfaction in the cooperative achievements of a group, and is less so to those who value an individual sense of achievement more highly. This ID picture is synonymous with the way in which much of industry tackles its development and engineering work. It also is more typical of short-term (e.g. up to 5 years) research than of the longer term.

Factors Aiding Interdisciplinary Coupling in Materials Science and Engineering

Individuals from different disciplines can work most effectively with each other if they have a common language. The materials field provides several such common languages which transcend disciplinary boundaries. These languages provide an intellectual catalyst for ID efforts.

The common languages include basic theories and concepts about solids, materials-processing methods, experimental techniques and instrumentation, and computer applications. Such languages emphasize the features that are common to metals, ceramics, plastics, electronic materials, and natural products. Some examples of these common languages are described below.

Basic Theme and Concepts

There are some basic physical models of solids which have been shown to apply to many materials. One of the most important of these is the recognition of the defect nature of solids. At one time it was thought that single crystals were nearly perfect geometric arrays of atoms or molecules in the particular structure revealed by x-ray diffraction. Through experiments on single-crystal filaments, on semiconductors, and other work, it has been shown that practically all solid samples contain important defects. Many of the properties in turn, particularly electronic, optical and mechanical, are dominated by the defect structure. The concept of defects in solids is a fundamental building block in understanding the behavior of any solid material. Chemical impurities are a special type of defect. The importance of an impurity to both the chemical and physical properties of solids has been revealed particularly through the extensive studies of semiconductors and metals, and is now being applied to other materials.

The idea of a band structure is another unifying concept which has been proven in studying many types of materials. Phase relations and thermodynamic equilibrium have also played key roles in greater understanding of conductors and insulators of crystals and amorphous materials. The concepts of nucleation and growth, of diffusion and segregation are applied to many classes of materials. Studies on the deformation of metals have provided essential inputs to understanding the deformation of ceramics and glasses. The idea of a domain has played a major role in magnetic and ferroelectric materials which, in turn. may be metallic or ceramic. Another example of a prevailing physical entity is the grain boundary. On its simplest level, the grain boundary is an array of dislocations caused by the intersection of two single-crystal regions oriented at an angle with respect to each other, but they are usually much more complex. Grain boundaries are of dominant importance in any polycrystalline solid regardless of its material or classification.

Materials Preparation

The methods of materials preparation have also been a factor in minimizing the differences between the old materials classifications. The development of solid-state devices requiring highly purified materials was built upon the knowledge gained of segregation at a solidification front as studied earlier in metals. Techniques for growth of crystals of one particular type are often shown to have much more general application. The advent of complex materials-preparation schemes such as the combination of high temperature and high pressure leads the investigator to search for opportunities to exploit his technical investment in other types of material.

Experimental Techniques and Instrumentation

Basic science couples very closely with MSE in the area of diagnostic tools for direct measurements of phenomena occurring at the microscopic and atomic levels. In the past it has been basic research, particularly in all branches of physics, which has given rise to the new and powerful measurement techniques, and it is to be expected that this will continue in the future. Many of the newer diagnostic techniques are sufficiently difficult to master that individuals specialize in the technique itself. The unifying influence then results from the natural desire of the investigator to apply his instrumentation to as many different materials as possible.

A related factor bringing together an unifying approach to all materials is that of evaluation and nondestructive testing. Again we see detection methods developed over the past few years which are applicable to many types of materials. Examples are gamma ray and neutron inspection, helium-leak detection, infrared imaging, holography, ultrasonics, and acoustic emission.

Computers

Another development having a strong influence on the unification of MSE is the high-speed digital computer. Most materials problems are complex, and particularly so if they are involved in engineering application. Only rarely does one encounter a materials problem in which the important phenomena can be treated in a mathematically simple way. As a result, until recently, it was necessary to make grossly simplifying assumptions in order to yield a mathematically tractable problem. More often than not, these simplifications were strongly material dependent and, therefore, highly restrictive. With the aid of high-speed computation, it is now possible in some cases to start with fundamental principles and to keep track of many of the complexities of a real material in analyzing its properties in terms of structure and composition. Not only does this elucidate the relation between the scientific knowledge and the external behavior of a materials, but also revealed is the common dependence of diverse materials on the same scientific models or concepts.

Importance of Purpose

A hallmark of a continuingly successful R & D organization is a clear recognition by all concerned of the overall long-term purpose, mission, or theme of the organization. Success of inhouse governmental laboratories and industrial laboratories in MSE has reflected especially the degree to which the overall mission of the laboratory has been defined, understood, and accepted, so as to provide a central interest that draws professionals from different disciplines together and provides continuity in basic studies beyond the span of individual development projects.

In striving to follow the overall purpose of an organization, there are usually tempting opportunities into byways which often have to be resisted. Otherwise, the greater goals would become fragmented and the main capability to focus a diversity of knowledge from many fields of science and engineering into a joint effort toward an ultimate goal would be badly obscured.

As Dr. Alvin Weinberg of Oak Ridge National Laboratory has stated, “a research institution must have a purpose that transcends the individual purposes and aspirations of its scientists; that it can fulfill its purpose only insofar as the separate disciplines and techniques interact with one another to produce more than they could achieve working in monastic isolation.”

The notion of a combination of gifted people from various disciplines of science and engineering, working together intimately but independently, is an institutional approach which has arisen almost entirely in the past few decades. A clear understanding of the institutional objective on the part of the assembled community is vital, but the objective must be very carefully chosen and stated—it must be sufficiently important, suitably broad, and technically meaningful that talented individuals will be inspired by it, challenged to help achieve it, and rewarded by a sense of worthwhile accomplishment as progress is made toward the goal. The continuing overall purpose of an organization may well be in the areas of human needs. Themes such as energy, transportation, defense, health services, communications, are broad enough to draw on many disciplines, yet specific enough to give all a sense of mission.

Such themes serve in a variety of ways; they can foster cohesiveness in an organization and help create an esprit de corps; they can facilitate decision-making as to which course to follow in research, personnel and program planning, etc.; and they can add even further zest to the most basic of the research activities. The latter point is especially noteworthy in that basic research often flourishes, and even the scientists themselves become specially intrigued, when a connection can be traced between the basic research and important new applications—for example, trying through basic research to determine what limits the superconducting transition temperature of a material is spiced by the realization that a breakthrough in the theory might have tremendous consequences for energy technology.

Interdisciplinary themes such as those just mentioned, while common in industrial and governmental organizations, are still relatively rare on the unviersity campus. Yet they would appear to offer challenging and timely opportunities for academic evolvement. COSMAT believes that there is an urgent need for university science and engineering departments to devote at least part of their resources to advancing the frontiers of interdisciplinary research and education in areas of technology that relate to societal requirements. There is a need to develop a better balance between the interdisciplinary and the disciplinary activities in academia.

COSMAT also sees no reason why the selection of appropriate themes for foster effective interdisciplinary activities should compromise the traditional academic standards of quality and freedom. Interdisciplinary research need not be of inferior quality to the traditional research by an individual—often the converse will be true.

Institutional Aspects of Coupling

Departmental Composition

The effectiveness of interdisciplinary MSE is influenced by the climate in which it operates. The climate is set by the organization. The special approach of MSE originated at, and has been most effective in, large R & D organizations in both industry and mission-oriented governmental laboratories. In those establishments, materials developmental problems have been relatively clearly identified and have been closely coupled with functions, designs, and applications. The management of such organizations has had the flexibility to involve appropriate individuals of various disciplines as required to solve the particular problem. Such goal—or program-oriented institutions do not accept the constraint of organizing by disciplines, but rather are guided by the talent requirements to accomplish the mission. Thus, strictly disciplinary groupings in departments are avoided. Functional groups covering a broad range of MSE areas are established which, in turn, couple with project groups aimed at specific objectives.

Geographical Barriers

Geographical separation between individuals and groups engaged in MSE programs should be minimized. Wherever there has to be a geographical separation, other ways have to be found for maintaining close communication. Common management is a frequent mechanism. Organizational and functional arrangements to be avoided are those which simultaneously create geographical separations and separations by discipline, or by research versus development versus engineering.

Size of Organization

Small organizations, industrial or governmental, may be able to support only small programs in MSE if the usual commercial factors are operating. These small programs then have to be very directly related to the product-objectives of the organization if they are to be regarded as cost-effective—the outcome of, and time scales involved in, more basic research programs are generally too uncertain. But in large establishments engaged in complex technologies, there is a much greater chance that results from various MSE projects will find applicability somewhere in the range of technological activities that the organization is concerned with. Size is, therefore, an important parameter, particularly as it affords flexibility to form new groups and mixes of personnel as new requirements arise.

However, sheer size of the organization is not a guarantee of success in its various projects. In its study of successes and failures in innovation in the chemical and instrumentation industries, Project Sappho revealed that perhaps the most important factor for success was the size of the project group rather than the size of the organization. A large organization spread over many subcritical size projects could fail; in other words, selectivity and concentration seem desirable. Clearly, in a small organization, it is critical that the right project be selected, and therein lies the principal risk, whereas in a large organization care must be exercised to see that programs are adequately manned.

A corollary to this discussion is that, generally, small organizations are not justified to engage in basic materials research but have to concentrate on development, engineering, and marketing—entrepreneurship. However, to do this still requires individuals who are able to interpret and exploit the results of basic research performed elsewhere.

Member-of-the Club Principle

For effective communication of knowledge and information between institutions, the receiving institution must be “tuned” to the transmitting institution; it must be staffed with some individuals and support some materials programs rather similar in quality and content to those in the transmitting institution. Otherwise, the receiving institution would be less able to interpret, understand, or exploit any of the information it received.

By maintaining individuals and programs at the institutional interface, an organization is able to respond quickly to new developments wherever they occur?

By the same token, an institution must generally expect to generate and transmit new information itself if it is to receive information in kind from other sources. Thus, for example, an institution that performs and publishes the results of basic research is, in effect, paying its “subscription” to the national and even international basic research “club.” By so doing, the institution puts itself in a position where it can more rapidly assimilate and exploit new research results the moment they appear. By not paying its “subscription,” an organization will tend to trail behind those that do, often having to rely on patent-right and royalty negotiations rather than on original invention for its economic health.

While the above remarks are couched to apply to institutions, they apply equally to the country as a whole. National competence in all aspects of MSE is vital if the U.S. is to maintain its position vis-a-vis other countries with such competence.

The principle also applies particularly to the industry-university interface. If industry is to make best use of the fruits of basic research in the universities, it must undertake some comparable programs itself. Failure to do so can lead only towards two non-communicating cultures.

Some Human Aspects of Coupling

Key Individual

A study made in 1966 and reported in Principles of Research-Engineering Interaction,[4] identified the importance of a "key individual." In a detailed study of a number of case histories, the Tanenbaum Committee found that one of the most common elements in programs of successful innovation and transfer of technology to practical application was a key individual. This individual played the role of champion for a particular idea or cause and appeared to be a necessary, if not a sufficient, factor for overall success in the program.

In reviewing successful examples of materials R & D, we also find that the key individual is important. To achieve coupling between science and engineering or between different disciplines, some one champion has to have the interest, understanding, and ability to span the entire program with some minimum level of competence in all sectors. The technical contributions in materials R & D are normally made by professionals who have highly specialized in a particular discipline. The additional element in materials R & D is that the same individual, although highly specialized, must also develop some appreciation and perhaps understanding for the contributions needed from other disciplines to solve the common problem. If a given program is large, requiring several individuals in the materials and applications groups, or if the problem is of such a nature as to require a wide spectrum of disciplines, then the key individual or champion must have an unusually wide span of interests and knowledge. Thus, at least one individual in the group must have an intimate understanding of the overall program and how the various elements will combine for the ultimate solution. It is tempting to assume that here is the proper place for a generalist. In practice, we find that the key individual is usually himself competent in some specialized field, but in addition, he has made an effort to understand in some depth the nature of the problem and the character of the solution for each of the disciplines involved. At the same time, the key individual, if a scientist, should also appreciate the engineering constraints, or if an engineer, be conversant with the scientific aspects of the problem.

Throughout this report, we emphasize the coupled nature of materials R & D and the crucial importance of contributions from various disciplines. While recognizing the advantages of such a group effort, we must at the same time note the irreplaceable value of a collection of knowledge and understanding in one mind. The one mind identifies the key individual in materials R & D.

Personal Satisfaction

The practical problems of the materials world are complex and normally require the insight provided by more than one specialty or discipline.

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[4] Report of the Ad Hoc Committee on Principles of Research-Engineering Interaction, MAB-222-M (1966), NAS-NRC, Washington, D.C.

Furthermore, the interaction between two or more disciplines can establish a synergistic climate for creativity. As already pointed out, success of the interdisciplinary group depends very much on a clear definition or a well-defined common goal and the acceptance by the group members. But in addition, it is also desirable to manage the effort in such a way that each professional member is in a position to make an individual and identifiable contribution in his own specialty.

All members of the group should have some breadth of view and appreciation for the importance of contributions being made by other specialists. Yet, to the extent that any member prefers to maintain his disciplinary identity, he is likely to be better motivated if he sees the possibility of receiving recognition for his personal contribution.

Nature of Groupings

There is danger of confusing the team approach which is characteristic of any large development or engineering program with the interdisciplinary approach characteristic of materials R & D. For a large project which must be completed in a limited time, it is necessary to organize a team of individuals in order that the job can be accomplished. The requirement may simply be one of assigning sufficient manpower to complete the total work in the given time. An example might be the development of a new computer software system. This might be accomplished by appointing a lead system programmer and assigning a number of other programmers to support him by carring various parts of the overall project. Similarly, in preparing the plans for a large building, the job could be broken down so that one architect might be responsible for one part of the project, another architect for another part and so on. One can readily think of other examples where development requires a team approach in which all the personnel are of essentially the same discipline.

Materials R & D is normally carried out in a group approach, too. It is often associated with development programs whose magnitude and time scales require a number of individuals to complete the job within the allocated time. What is special about materials R & D, however, is that different disciplines must usually be focused on the same problem in order to achieve a solution. The difference between the team approach and materials R & D becomes most apparent in the extreme of small groups. In the small group limit, namely, two persons, the team approach often has two individuals of the same discipline and training; for example, two aerodynamicists or two chemists. Materials R & D on the other hand, tends to converge on two individuals with different disciplines and training. Examples of such pairs are a physicist and a metallurgist; an aerodynamicist and a thermochemist; an electrical engineer and an inorganic chemist; and a metallurgist and a structural engineer. Thus, it is the interdisciplinary element which is important, not just the combination of two or more individuals.

Supervision of Group

The question of leadership or supervision of an interdisciplinary group deserves much emphasis, but at the same time is hard to describe precisely. Supervision of an R & D activity is difficult, but that of materials R & D has an added dimension of challenge.

In a typical development program, the project is organized under a project leader and consists of several professionals to accomplish the objectives in the time allotted. The supervisor must himself be technically competent, must be sensitive to the originality and judgment of the members of his group, and should have that undefinable quality which provides leadership rather than just direction. Nevertheless, in such a group there is a clear understanding of a supervisory-subordinate relationship. In the case of interdisciplinary materials R & D, the added complexity derives from the need for a group to act as an individual. No longer is there the neat arrangement of a project leader, but rather a way must be found so that the inputs from several members can have even weight. This requirement for a true group effort results from the very nature of the interdisciplinary problem which demands significant inputs from two or more disciplines. The very quality most needed can be destroyed by an insensitive attempt to “direct” the work for more “efficiency.”

Coupling Through Mobility of Personnel

Coupling between organizations or between separate locations within the organization is a critical problem in materials R & D. Without question, the most effective coupling between separate groups has been accomplished by the movement of knowledgeable and involved individuals. Although the documentation and publication record is good in materials R & D, there is no way to transmit on paper the many subtleties and sensitivities connected with the processes for producing new materials with special properties. Experience has repeatedly shown that a complex new materials process developed at one site can more easily be transferred to a different manufacturing location if some of the key individuals are also transferred. If that is not possible, then special attention must be taken to assure adequate transfer of technology from one site to another. Industrial organizations and governmental agencies solve this problem by, first, defining clearly the required objectives, second, by supporting extensive travel between the two sites, and third, by applying special management effort. The experience of the ARPA university-industrial coupling programs illustrates the difficulty of achieving effective interaction when compelling objectives common to the two locations are missing and where there is little or no personnel movement. The problems experienced in this ARPA program do not in any way reduce the need for more effective cooperation between university and industry. It does emphasize, however, that coupling is something more than just good technical work. Attention must also be paid to perceptive management, to acceptance of common goals, and to the time required for person-to-person contacts and intergroup working arrangements to mature. Further experiments on university-industry coupling are urgently needed.

There are good examples of close coupling between materials R & D and the design or application engineers in industry and government. On campus, however, this coupling tends to be weak. The traditional academic structure, with departments matching disciplines, militates against this type of coupling, and there is normally no funding to support joint efforts by the materials and design sectors of the faculty. Ways should be found to try block-funding for two or three faculty members in a joint effort to couple materials development with design for a specific product or service.

Consulting arrangements have been helpful in coupling university-generated knowledge to industry and governmental agencies. Joint appointments, where the same individual works both on and off campus, may be even more effective. The industrial community in materials R & D appears only weakly coupled to academia, partly because of the relatively small numbers of experienced materials development people who participate in regular faculty activities. The shifting of individuals from one location to another is an important element of coupling within an industry. This was particularly true during the rapid development of the new solid-state industry when many Bell Laboratory solid-state specialists moved into newly emerging commercial firms and also to a number of campuses. A dynamic, two-way flow could further enhance information transfer in MSE.

Roadblocks to Effective Coupling

Many of the obstacles to effective coupling can be inferred from the preceding sections but a few additional comments are in order.

In the early stages of an interdisciplinary materials program, the group may be composed mainly of basic research scientists with a relatively small number of engineers. As the project progresses towards application, more engineers may join the group while the basic research scientists may drop off and move on to other programs that are starting up. Such an evolutionary sequence in the R & D spectrum provides a very effective way for surmounting the "not-invented-here" syndrome so often characteristic of programs in which the research, development, and engineering are done in sequential stages by different groups or departments.

The literature on interdisciplinary research contains discussions of other roadblocks, too, as well as the strengths and weaknesses of interdisciplinarity. A particularly useful summary of the pros and cons appears in "Interdisciplinary Research—An Exploration of Public Policy Issues."[5] Though the study is primarily concerned with the problems of interdisciplinary research involving both the physical and the social sciences, many of the conclusions are directly applicable to MSE. Some extracts from that study are given in Appendix 3K; p. 3–97.

IMPLICATIONS OF MATERIALS SCIENCE AND ENGINEERING FOR UNIVERSITIES

Education in Materials Science and Engineering

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[5] Report prepared for the Subcommittee on Science, Research, and Development of the Committee on Science and Astronautics, U.S. House of Representatives, by the Science Policy Research Division; Legislative Reference Service, Library of Congress, October 30, 1970.

Every professional field requires individuals of high caliber with regard to intelligence, insight, creativity, and motivation. MSE is no different. Actually, however, it must operate successfully with its fair share of the distribution of the available talents among professional people. The more meaningful question then becomes: What training and experience can be expected to supply effective contributors in the field of MSE?

Materials development is complex. In spite of the success of science in unifying the field, there still remains an amount of empirical knowledge which must be known by the practitioner. Furthermore, an individual knowledgeable in one aspect of the field must have a good working appreciation for the contributions which can be made by other disciplines and specialties.

We have repeatedly emphasized the multidisciplinary and interdisciplinary nature of MSE and the requirement for individual contributors to be highly specialized in particular areas. Metallurgy, ceramics, and polymerics appear to be merging toward a common discipline; but the range of materials problems faced by MSE is so vast that other disciplines such as electrical engineering, structural mechanics, physics, chemistry, medicine, and biology will continue to contribute in many important ways.

To illustrate the varied concepts and viewpoints which different disciplines bring to a problem, Table 3.2 lists a number of characteristics or attributes which are commonly associated with three disciplinary fields. From this listing, it is obviously unreasonable to expect one individual to fully absorb all of these different viewpoints and concepts to the degree that he can compete with specialists in any one field. Moreover, these are not the only disciplines which contribute to MSE; Table 3.2 is not meant to be restrictive or exclusive but only tries to illustrate the differences among disciplines.

It is helpful to distinguish between those individuals who generate new knowledge in MSE and those who apply such knowledge. There is a basic difference between these two activities and that difference must be reflected in the training which is appropriate.

The creation of new knowledge implies that the investigator is fully informed of preceding work which has been done in his specialty. In addition, he must have mastery of analytical and experimental techniques peculiarly suited to his line of investigation and, above all, the time for careful measurements followed by detailed analysis and intellectual scrutiny. Therefore, the logical preparation for a substantial number of contributors in the future will be at the doctoral level. The heavy content of science in MSE makes the higher-level degree a natural training route for those who will attack the most basic problems in the field. During the past dozen years, academia has been remarkably effective in preparing individuals for careers in materials science by training at the masters, doctoral, and postdoctoral levels. The establishment and support of the interdisciplinary materials research laboratories played a central role in this response of the universities to emerging needs of technology. The high level of accomplishment in materials science needs to be maintained, but it is also time to recognize that the broad spectrum of MSE should be fully reflected in the academic educational program. In particular, materials engineering now requires similar upgrading, emphasis on interdisciplinarity, and major facility investment which materials science has enjoyed through the interdisciplinary

TABLE 3.2 Comparative Characteristic and Attributes of Some Disciplines Involved in MSE

Those trained in physics tend to:	Those trained in chemistry tend to:	Those trained in materials, metals, ceramics, polymers, tend to:
Isolate the problem until it is susceptible to quantitative treatment.	Use some theoretical models, but depend more on correlations, classifications, and comparisons to deal with chemical problems.	Accept complex problems associated with practical needs.
Seek rigorous treatment of relatively simple systems.	Accept a relaxation of rigor necessary to allow treatment of complex systems.	Adapt theory from physics and chemistry but add empirical approach to achieve results.
Propose theoretical hypotheses to be followed by experiment.	Place emphasis on experiment; theories often phenomenological.	Make extensive observations followed by empirical relationships, rules, and theories.
Know a few basic concepts applicable to many phenomena and relationships.	Use basic concepts plus laws on composition, thermodynamics, and kinetics (statistical wiping-out of detail).	Use elemental concepts plus general guiding principles or rules plus experience and knowledge of material classes
Have confidence to attack any physical science problem.	Have knowledge and experience to solve chemical-related problems in most efficient way.	Have the interest, knowledge, and experience to solve practical problems within time and budget limitations.
Center interest on how or why something happens.	Emphasize the material. Be interested in how of why, but oriented to application more than basic understanding.	Place emphasis on the material, including practical matters of manufacturing. Be interested in utility; desire to deal with real-world problems.

Those trained in physics tend to:	Those trained in chemistry tend to:	Those trained in materials, metals, ceramics, polymers, tend to:
Use zero-order approximations or idealized representations to identify important factors.	Use models plus intuitive reasoning based on experience.	Deal with multiphases, partial crystallinity, grain size, texture, defects, and thermomechanical history.

laboratory programs.

An individual whose principal function is the application of knowledge relating structure, properties, and processing to materials function and performance can contribute with a broader and less specialized training. His aim is to understand existing knowledge in MSE and to determine how it can be applied to new products or designs. In such an objective, he will naturally be more oriented toward processing and product across the entire field of materials. The larger share of practitioners in MSE are found in this category because new knowledge in the field can be appropriately applied in many different situations. The generalist is particularly suitable for the smaller companies which do not have the resources to develop new materials properties as a normal part of product development. Because of the breadth and complexity of MSE, the masters level has become appropriate for those who will be mainly concerned with applications in the field, but even here, there is increasing attention to doctoral programs.

Because MSE, in the main, is a purposeful endeavor, it is desirable that students slated for advanced degrees should acquire some working contact with practical materials problems during the course of their education. One method which has worked well is the cooperative program in which a student alternates between an industrial job and a period on campus. This scheme has been used primarily at the undergraduate level where the candidate may be limited in the skills which he can apply to a technical assignment. Nevertheless, most graduates of such programs feel strongly that they were benefitted in understanding how their academic training could be put to use.

Another excellent way for a student to gain some firsthand understanding of practical problems is summer employment in an industrial or governmental laboratory. This can be accomplished when the student is further along in his academic training and can, therefore, contribute more effectively. The completion of the B.S. or the first summer in graduate work may be convenient break points. It is hampered to some extent by both students and faculty who regard the summer away from campus as an interruption in the graduate program. A broader view might suggest that such experience is an integral part of the educational process in MSE and should be balanced with the academic courses and research training on the campus.

Unfortunately, programs for student work experience in governmental and industrial laboratories suffer severe cutbacks during economic recessions. However, this in no way reduces the importance of this educational component. Substantial effort should be devoted to creating opportunities for MSE students to gain practical experience before completion of their academic training.

University Research in Materials Science and Engineering

The materials research performance of the universities in this country has been mixed. The output of fundamental materials science in academia has in aggregate been excellent. However, materials research in the interdisciplinary mode has not faired quite so well when compared with the better industrial and governmental laboratories. The universities have two cardinal principles which interfere with interdisciplinary materials research on campus. Each principle is securely based on centuries of experience in education. The first is the organization of the university by branches of learning, in other words, by disciplines. Once the disciplines such as physics, chemistry, or metallurgy have been established, the very nature of organizations and human beings is such that close cooperation within a discipline is more easily accomplished than across disciplines. In addition, the main peer groups off-campus are the professional societies which tend to be discipline-oriented. Thus, both peer evaluation and rewards are structured along disciplinary lines.

The second cardinal principle on campus is the pre-eminence of individual contribution. Scholarship and creativity are most easily identified and evaluated when they can be attributed to a single individual. On the other hand, for some problems originating in nature and in society, such as many of those in MSE, a joint effort may be required for effective solution and the campus has not been a ready setting for such an arrangement. If materials research is to be adequately performed at the universities, then some modifications in the funding, traditions, and reward system are required. However, if the universities are to serve mainly as training grounds for professionals in MSE, then simply a change in emphasis and motivation may be required. After all, the universities do not feel obliged to run businesses on campus in order to properly train future business leaders.

Materials research is generally interdisciplinary in nature when conducted in industrial or governmental laboratories. Materials research laboratories on the campus, therefore, are ideally situated for bridging between the traditional discipline-oriented activities of universities and the interdisciplinary activities outside the campus. But too frequently these laboratories have failed to take advantage of their opportunities along these lines. Instead, they have often served to provide additional support on campus to the traditional activities organized by discipline. For example, central facilities such as electron microscopes and crystal-growing laboratories are not being used in an interdisciplinary way if physicists, chemists, metallurgists, and so on, simply take turns at using them rather than apply them to truly collaborative researches. In general, a major aim of materials research laboratories should be to provide opportunities for members from the vatious disciplines to undertake, when appropriate, interdisciplinary, collaborative programs, but by no means should every individual be required to be engaged in interdisciplinary work all the time.

Materials research laboratories can offer an effective meeting ground for professionals of different disciplines where joint programs can be initiated and research results obtained which none alone could achieve. A good stimulus for such collaborative efforts is for the center, or a section of it, to have a broad technological focus which serves to promote a common interest among individuals from different scientific and engineering disciplines. Some centers may choose to focus on electronic materials and relate to the electrical engineering departments, others on biomaterials and relate to medical departments. Still others may elect broad themes such as energy or communications. When astutely chosen, such themes can embrace a wide range of scientific and engineering activities; they are not unduly restrictive but rather stimulate further intellectual interactions, and for those who desire it (possibly a growing proportion), they provide a connecting thread between pure scientific endeavor on the one hand and usefulness to society on the other. COSMAT feels that universities possess, with their materials research laboratories, vehicles that offer exciting opportunities for interplay between traditional academic pursuits and societal needs. It is important to insure that these laboratories make the most of their opportunities.

Funding and Reward Mechanisms

In the traditional academic departments, it is usual for individual faculty members to seek their own research grants and contracts. Such practice is less useful in interdisciplinary research projects which are more subject to changing external requirements. An effective support mechanism for such programs is forward block-funding administered by local laboratory management and subject to outside review. Block-funding provides flexibility for adapting to the varying needs of different interdisciplinary programs and also provides a source of seed money for new ventures.

It is important to the success of interdisciplinary programs that there be recognition and reward schemes which compare with those accorded the traditional disciplinary areas. Universities appear to have much to learn in this respect, and are generally behind their industrial counterparts.

OUTPUTS OF MATERIALS SCIENCE AND ENGINEERING

What are the outputs of MSE? First, and most obviously, the answer is new materials, new processes, new materials systems, and improvement in the existing technology of materials. In either its creative or responsive mode, MSE has as an overall major objective the development of a material which meets particular application requirements or opens up new application opportunities.

Secondly, MSE has an output which is additional understanding in the field itself. When the scientific approach is used, the new understanding and findings from a given project can be generalized and applied to a wider class of problems. As an example, the early studies on segregation at the solid-liquid interface in metals were later applied to the purification of semiconductor materials for electronic applications. Zone refining as it was then labeled has since been applied to the purification and compositional control of many other materials.

A third output of MSE is the identification or stimulation of an area for expanded fundamental research. Sometimes the work being done to meet particular materials goals uncovers a phenomenon which had not been previously reported and which cannot be readily understood. Such unanswered questions are the livelihood of fundamental research. In other cases, materials development for a specific need may arouse new interest in a particular area of basic science.

Yet another way in which MSE can stimulate fundamental research is in the creation of new techniques, instruments, or machines for the production of certain materials. One example is the making of synthetic diamonds by high-pressure, high-temperature conversion of graphite to the diamond form. Successful synthesis of diamonds required the development of new high-pressure apparatus whose capacity extended far beyond that of the classic work of Bridgman. The announcement of commercial quantities of man-made diamonds dramatized the practical importance of high-pressure technology. Moreover, the new high-pressure techniques also became available to the entire technical community. As a result, there was a sudden increase in studies on the effect of high pressure on material properties and on the synthesis of new materials at high temperature and pressure. Similarly, the discoveries of the bistable nature of the conductivity of certain amorphous materials led to a flurry of fundamental investigations attempting to understand the exact nature of conductivity through amorphous materials and the influence of high local currents.

In a very general way, the broad field of metallurgy has identified the problem of oxidation and corrosion. A large volume of research is now addressed to the basic chemical and physical phenomena involved in oxidation and corrosion.

The success of medical implants, such as plastic tubes to repair arteries, has kindled a new field of fundamental study. Although successful in many cases, such plastic implants suffer two major problems, namely abrasive degradation of blood cells and undesirable clotting. As a result, investigators are now examining the basic physical, chemical, and biological reactions of such surfaces.

Most glasses are permeable to helium even at room temperature, a property which gives rise to problems in glass vacuum envelopes. This knowledge was turned to advantage when the U.S. faced a severe helium shortage. Suitably designed glass tubes at elevated temperature were used as helium-permeable membranes to extract the noble gas from the discharge of certain natural gas wells. This dramatic solution of a problem of central interest throughout the scientific community served to direct new attention to the fundamental question of precisely how gas is transported through amorphous solids such as glass.

MSE also has a widespread output in the more efficient design or improved performance of many existing products. This transfer of a capability designed for one program to another application is a form of spin-off. There are few sports or leisure activities which have not felt the impact of materials developments during the past two decades. Snow skis and water skis use fiberglass construction; sailboats fly dacron sails; tennis rackets are made of high-strength aluminum alloy and the stringing is nylon; football fields are covered with turf woven from artificial fibers.

MSE has even generated entire consumer industries. One of the most dramatic is the artificial fiber industry which now outproduces the combined output of cotton and wool in this country. Of equal importance is the synthetic plastics industry to which MSE has contributed heavily. Another large and growing sector is the solid-state electronics industry, whose origin rests squarely on MSE. Still another relatively new and rapidly expanding industry which touches on the daily lives of most Americans is the office copying machine. The development of the electrostatic photocopying surface fully meets all of our criteria for the definition of MSE. The tape-recording industry is another example of the creation of new commercial activity which rests upon the development of new material capabilities. This has benefitted the music world, both in radio transmission and in home reproduction systems. MSE has also played a vital role in large-scale computer systems and in the television industry.

NEW OPPORTUNITIES FOR MATERIALS SCIENCE AND ENGINEERING

Changing Nature of Materials Science and Engineering

Like all science, engineering, and technology, MSE is changing rapidly with time. It is necessary that we identify the trends in the materials field in order that we can project these into the coming years. Our study has revealed the growing incidence of interdisciplinary projects in MSE. A few decades ago there were isolated instances of such work; in recent years, examples have been more frequent. We believe that an important trend has been established, a trend which should be accelerated.

Review of a number of case histories has shown that science-intensive programs have been the most likely candidates for the practice of this interdisciplinary mode. Such programs had two characteristics in common: (a) The project had established overall objectives which could not be met with existing materials. This statement has categorical success-or-failure signifance and is contrasted with many development programs in which materials development might make only an incremental contribution to better performance or lower cost. Examples which come immediately to mind are nuclear-reactor fuel elements in which materials and methods had to be devised to contain radioactive products, or the oft-cited transistor program which required an entirely new level of semiconductor chemical purity and single-crystal perfection, (b) A second feature of the science-intensive programs was that the entire effort had moved out beyond the traditional engineering achievements. New approaches were required. This created a climate of more-open consideration of new ideas, concepts, developments, and changes. Within this open framework, the materials specialists were in a better position to interact strongly with the applications engineers and to make the kinds of trade-offs which have been described here earlier under the systems approach.

This interdisciplinary mode, however, has not existed solely in the glamour projects. In some instances, we find individual companies or sectors of the economy where a challenging new goal has been internally generated, and where these internal goals have been sufficiently demanding to require a science-intensive approach for their solution. Some examples are the development of polymers-coated razor blades, the creation of the synthetic fiber industry, and the integrated-circuit business.

In reviewing the trends of MSE, one must conclude that the contributions to society have been considerable but uneven; that is, some have been served more satisfactorily than others. One of the themes which has emerged in the COSMAT study is that MSE is motivated by and is responsive to societal needs. In some cases, specific needs have led to increased scientific investigation and understanding as, for example, in the problem of oxidation and corrosion of steel. But scientists usually prefer to work on problems which yield good opportunities for scientific advances, and societal requirements have often been too complex to offer much promise of scientific reward. In such instances, the trial-and-error approach or merely dependence upon past experience has had to suffice.

If we now try to project the future of MSE, it is clear that several factors combine to continue and possibly accelerate the trend toward the interdisciplinary approach which has already been established. First of all, we are rapidly obtaining greater scientific knowledge and capability, especially in the fields that apply to materials. Since science feeds on its own previously acquired knowledge, this buildup in understanding is an autocatalytic phenomenon and provides a common language which links the various parts of the materials field. The eventual result will be a science and engineering of materials which is capable of handling a much broader range of problems, even those of societal complexity.

At the same time that the capabilities of MSE are rising, the manufacturer of any product is under pressure from many quarters to squeeze more performance out of his materials. He is asked to hold prices in the face of rising labor costs, to process materials without hazards and pollution, to satisfy increasing customer demands for product quality and reliability, and to relieve pressure on dwindling sources of raw materials. In more and more cases, these conflicting demands will result in a requirement for new material or process capabilities. As time goes on, it is likely that some of the industries which are now clearly experience-based will be forced to rebuild on a science-base. Historically, knowledge has diffused to new fields. If there are experience-based industries in which the old ways are too firmly entrenched, the science-based approach will enter by some other industrial segment taking over.

Increased labor costs will undoubtedly exert a strong influence on the activities in MSE. The role of materials resources and processes which are labor-intensive will inevitably decline. The ever-increasing cost of individual repair work will lead to emphasis on material properties not only for first manufacture but also subsequent repairability. Similarly, it may be expected that designs will be modified to facilitate easy repair by the user.

Thus, all indicators seem to point to increasing emphasis on materials development which makes maximum usage of scientific understanding closely integrated with design and application in the broad sense, and which is fully balanced with regard to the overall materials cycle.

Changing Industrial Scene for Materials Science and Engineering

Many of the outstanding advances in MSE have been achieved by industrial organizations making it a practice to support comprehensive, suitably balanced, and coupled R & D programs. Such industrial accomplishments include the discovery and subsequent development of nylon, the transistor, the high-field superconductor, the laser, color phosphors for TV, high-strength magnetic alloys, magnetic ferrites (Netherlands), polyethylene (U.K.), and so on. What is noticeable about these breakthroughs is that they took place in companies that supplemented the traditional, experience-based approach to materials and product development with science-intensive research programs aimed at building the body of knowledge on which the technology was ultimately based. These companies established leadership, both for themselves and for the nation, by not leaving this vital longer-range activity to other industries or laboratores, either domestic or foreign.

With the broadening emphasis on national goals, from aerospace, defense, and atomic energy to more civilian-oriented technologies, the practical objectives of industry are changing, but there is no evidence whatsoever that the importance and value of research will be diminished. Enough basis is presented elsewhere in this report to indicate the many fresh technical challenges facing industry in addition to those which arise directly from the growing problems of materials availability and concern over environmental quality. Many of the newer challenges can be met only with the help of a sustained, science-intensive approach; reliance cannot be placed solely on the experience-intensive approach, inasmuch as often there is no such experience. And the evidence of the past quarter of a century is that science-intensive or high-technology industry is a much more positive factor in the U.S. international trade balance than low-technology industry.

Yet, despite the proven long-term values of comprehensive in-house R & D programs, faced with the pressures of competition from other companies and other countries, the recent trend has been to reduce costs by cutting back on relatively long-range R & D, even in the science-intensive industries. The cut-back has been even more severe in the experience-based industries; what relatively basic research they did has been eliminated in many cases. Cutting back on R & D may improve a company's profit position in the short run, but it leads the company and the entire industry into a less dynamic and less innovative position in the long run. Furthermore, the company that continues to perform R & D may even see itself priced out of an eventual market by those companies who simply avoided R & D costs and instead went immediately into production using the results of the R & D performing company. Because this can happen in many instances, there is the growing attitude that the penalties for failure in an R & D program are too great, while the rewards for success are too easily appropriated by others, and hence too uncertain. For the company not in a position of leadership, it often makes most sense to obtain its new technology from other companies through cross-licensing or royalty agreements, for example; but for the company that is striving for leadership, investment in a balanced R & D program is vital. The same pattern has been developing on an international scale; while it was in the catching-up phase, Japan imported most of its new technological ideas. Now that it has caught up in many areas and is aiming at leadership, Japan is investing rather more heavily in R & D.

All programs in technology are influenced, of course, by the magnitude and arrangement of financial support. One such aspect of MSE needs special emphasis. The most critical stage in the development of any new material is in its transfer from the R & D laboratory to full-scale production. Successful transfer to production is a prerequisite for the contribution of any new material to society. At the same time, this is normally the most expensive phase of the program. Moreover, the depressed industries are often those which are in greatest need of innovation in materials and manufacturing processes. Foreign producers using new steelmaking processes developed abroad have impinged on the expansion of steel-plant capacity in this country. Already faced with unsatisfactory profits, it is difficult for the individual steel company to commit to major new plant investment as would be required for longer-term economic advantages. New ways must be found to promote the implementation of new manufacturing processes which can yield significant economic or environmental advantages. Added incentives are needed which, on the one hand, reflect the broader perspective of the nation, and on the other hand, retain the insight of the profit-oriented company. Plant investments for new materials and processes are normally major expenditures and the decision to commit resources for these purposes requires a climate which is attractive to significant risk-taking.

Changing Societal Goals and Support-Base for Materials Science and Engineering

At any given time, a society has a number of goals which receive priority. The method for establishing the goals is ofen not precise; but, nevertheless, a general consensus is somehow reached. Societal goals are a way of drawing attention to programs which require adequate allocation of resources and contributions from many segments of the society. Frequently, achievement of the goals depends on a strong technological input. In the period following World War II, the development of weapons, both nuclear and conventional, received high priority. Following Sputnik, the demonstration of technological excellence through the man-in-space project was a goal of our society. More recently, emphasis has shifted toward goals which more directly affect the daily lives of the general population such as energy, health care, transportation, environmental quality, housing and urban renewal. Dramatic progress in meeting these goals can only be achieved through considerable innovation, and much of that innovation will be in materials technology.

Economic strength of the nation is the foundation for attaining cultural improvements no less than for the elimination of poverty, the maintenance of world peace, or the capability, to aid developing nations. Innovation is one factor which has traditionally provided the U.S. with economic leadership in the world markets and with a rising standard of living at home. Innovation has spawned a number of science-intensive industries such as television, the airframe industry, computers, plastics, and many others. Innovation has also augmented economic strength by advances within established industries such as: communication by microwave links, wrinkle-resistant fabrics, self-developing photography, prestressed concrete, and many more. In most cases, innovation includes the development or modification of a material.

More and more frequently, interdisciplinary research, development, and engineering is proving to be the most successful, often necessary, approach to innovation. Opportunities for the lone inventor are relatively limited as evidenced by the percentage of patents granted to individuals not affiliated with a large company.[6] The sophistication of modern technology increasingly requires a group effort in which participants—each with specialized training and knowledge—jointly achieve innovation of significant impact. Therefore, successful practice of the interdisciplinary approach deserves special attention.

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[6] In 1901, independent investigators obtained 82% of all patents; in 1967, their share was only 23.4%. SSLA: Ekonomike, Politika, Ideolgiga, April 1971.

MSE will continue to play an important role in meeting our societal goals. It will often be a cardinal element in innovation, particularly in matters bearing upon energy resources, environmental control, and economic strength. In many examples, MSE has demonstrated the power of an interdisciplinary approach to solve difficult problems. Most of these examples are found in science-intensive technology programs. That is where the performance requirements on materials have been sufficient to demand the science-intensive approach for the adequate solution. Moreover, in many of these activities, the customer has been the government rather than the public market, and cost considerations have played a different role. It is interesting to note that the science-intensive technologies are relatively new; typically, there is no long established body of knowledge and well-identified group of practitioners. Rather, the nature of the problem causes a new cohesion to be formed. It is in this situation that the highest reception prevails for new ideas, new approaches, and the maximum utilization of science to reach engineering objectives.

Conversely, the long established activities are the ones where we find the greatest communication problem between the MSE practitioner and the traditional applications man. If MSE is to make significant contributions in experience-intensive areas which are of prime importance to the economy, ways must be found to support technical advances with mechanisms for adequate transfer of new technologies across a broad front of applications.

Until recently much of the federal support for materials R & D was by the Department of Defense, NASA and the AEC. These three agencies have accounted for some 90% of support for R & D in (metallurgy and) materials engineering in FY 66 and 81% in FY 71[7] (See Table 3.3). With regard to MSE, the three agencies had in common the pursuit of programs which were materials-limited. For example, in the DoD, the development of infrared surveillance devices required semiconducting materials with higher quantum efficiency and lower noise. In the AEC, the development of more efficient reactors required fuel elements for fast-neutron breeder reactors. In NASA, adequate rocket performance demanded control-vane materials with high-temperature strength and corrosion resistance never before attained. This list of three examples could be expanded almost indefinitely. In that technological environment, materials development was recognized as of central importance. Consequently, MSE has been supported extensively in the agencies' own laboratories, at universities, and in relevant industries, both directly and indirectly. Reduction of the total R & D effort in these three agencies can be expected to be reflected in a proportionate reduction of support in MSE. It is now appropriate to ask whether the capacity of MSE in the country, so released, should be turned to the new programs in response to societal needs.

On first look, it appears that the new governmental agencies such as HUD and DOT will not require the same proportion of MSE as have the defense, atomic energy, and space agencies. The new agencies will first need to go

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[7] This trend is consistent with the overall reduction of R & D support by defense-related and space-related agencies, 51.7% in FY66 to 39% in FY71 (NSF–70–46, Funds and Manpower in the United States 1953–1971.)

TABLE 3.3 Federal Funds for Total Research in Metallurgy and Materials Engineering in FY 1966 through 1971 (Est.)*

	Millions of Dollars							
Agency	1966		1967		1968		1969	
Total		153.434		120.588		118.206		140.703
Commerce (NBS)		1.523		1.563		1.367		2.185
DoD		98.198		60.405		54.317		63.220
Army	16.990		13.748		12.522		13.472	
Navy	20.562		14.010		16.574		17.948	
Air Force	31.458		22.525		18.608		24.398	
Other Agencies	29.188		10.122		6.613		7.402	
HEW		1.558		1.782		1.910		0.362
HUD		—		0.050		0.050		0.005
Interior		5.725		7.750		11.108		11.374
BuMines	5.725		7.750		10.977		11.344	
Other	—		—		0.127 (Genl. Surv.)		0.030 (Water Res.	
DOT		—		—		1.017		7.080
Aviation (FAA)	—		—		—		—	
Highway (FHB)	—		—		1.017		7.080	
Railway (FRA)	—		—		—		—	
AEC		24.537		25.515		25.216		24.427
NASA		17.487		19.533		20.591		25.790
NSF		2.287		4.181		2.577		3.202

* From NSF Federal Funds for Research, Development, and Other Scientific Activities, Volumes XVI–XX, 1967–1971.

	Millions of Dollars					
Agency	1970		1971 Est.		1972 Est.	
Total		151.549		154.734		159.750
Commerce (NBS)		1.928		2.013		2.012
DoD		71.359		73.916		82.124
Army	15.360		14.923		15.661	
Navy	19.030		19.973		24.848	
Air Force	27.139		28.053		29.215	
Other Agencies	9.830		10.967		12.400	
HEW		0.031		0.036		0.041
HUD		0.284		0.474		0.510
Interior		14.464		17.746		16.647
BuMines	14.448		16.827		15.297	
Other	0.020 (Water Res.)		0.950 (OCR)		1.150 (OCR)	
DOT		6.914		6.324		7.341
Aviation (FAA)	—		—		—	
Highway (FHB)	6.374		6.134		7.181	
Railway (FRA)	0.500		0.150		0.120	
AEC		30.986		30.950		30.320
NASA		22.458		21.178		17.633
NSF		3.020		1.987		3.060

through a phase of utilizing and applying exising knowledge. An example is BART in the San Francisco Bay Area, the first underground transportation system designed since 1907. BART required little, if any, new materials development. Similarly, there is no one major materials impediment to the construction of wide-scale, low-cost urban housing. In the health area, the largest problems of the present time center about the provision and distribution of medical services rather than the limitations of any one surgical procedure or treatment technique.

On second look, the situation is not that simple. As mentioned, the first phase of the new programs can make significant contributions by utilizing existing technology, including materials. As time goes on, however, needs will become evident for further materials development and refinement. Indeed, we already see examples in the area of environmental quality and pollution. Internal combustion engines emit among other things undesirable oxides of nitrogen. A suitable catalyst could provide for elimination of such a compound, but no satisfactory catalyst is now available. It would appear that new approaches are required. A quite different way to avoid the emissions from internal combustion engines is the use of the electric batteries for vehicle power. There is some indication that batteries with solid electrolytes might overcome the classical difficulties of battery-operated automobiles. At the present time, materials are clearly the limitation to this approach. The dangers of mercury pollution of water have been publicized in only the past few years. One possible solution toward the management of this low-level but toxic contaminant is through surface adsorption on solid particles; but the development of any practical, economic system awaits further understanding of surface states and the interaction of adsorbed particles with the substrate. These are but a few examples to make the point that the newly emphasized societal programs will definitely depend on contributions from MSE.

It is difficult to estimate the time which will elapse during the first phase of technology application via the new federal agencies. It is likely, however, to be of the order of five to ten years. This is just about the time scale required by the university community to respond in the training of students through undergraduate and graduate programs. There is some danger, however, that because of the recent technological and economic recession, the country will overcorrect on the rate of supply of new professionals for a given field and thereby undershoot the longer-range requirements.

The changing agency-base for governmental support in MSE has another important implication. The changing goals and programs forecast a shift in emphasis within MSE from science to engineering and application.

In the industrial segment the situation has also changed rapidly during the past few years. The technological trickle-down theory from scientific research has met with skepticism. It is now felt that considerable engineering and applications-oriented effort must be expended directly on the problem in hand to produce significant results. Some companies consider that they have created a backlog of scientific knowledge relevant to their business and must now spend proportionately more of their resources in applying this knowledge. The economic recession of 1971 has accelerated the realization that an individual company needs more engineering effort on its specific problems at the expense of science. At the same time many companies, particularly in the experience-based industries, could benefit from more science involvement in their development and production programs.

In the societal goals such as transportation, housing, and environmental quality, there are materials problems to be solved, but there are also many other impediments. Substantial gains can be obtained through a systematic engineering application of knowledge which is already available in some form. Therefore, the MSE contribution in these new areas will, for the first few years, be more engineering than scientific in character.

We are discussing here only a change in emphasis between science and engineering and by no means an elimination of the scientific portion of MSE. The big three agencies continue to support materials research a a high level. The nature of their objectives requires the continued expansion of materials science knowledge. Even for the newer societal goals, the demand for additional scientific understanding will rise as the existing relevant knowledge is applied in the early engineering accomplishments.

The more recent federal agencies such as DoT, HUD, and EPA do not have a long tradition of working with materials professionals. Program managers in the agencies may not be aware of the potential contributions of MSE. The MSE community should take the initiative in closing this gap.

Opportunities for Materials Science and Engineering in Some Areas of Concern to Society

We have already shown how MSE has been responsive to societal needs when these have been clearly expressed and adequately funded. The country's desires for new military technology, for exploitation of nuclear energy, and for the conquests of space have all been answered by important contributions in the interdisciplinary mode of MSE. Major industrial advances and creation of new industries, also related elsewhere in this report, have resulted directly from contributions in MSE. When viewed in today's perspective, the materials community might be criticized for giving inadequate attention to certain elements of the materials cycle such as pollution and recycling, but every evidence indicates that MSE will respond as new goals are defined and requirements spelled out. In the following chapter, the relations between MSE and several newly evolved national goals is described in sufficient detail to portray the kinds of contributions which MSE can be expected to make. At this point, however, it is appropriate to comment briefly on such areas.

Resources, Substitutes, and Synthesis

Resources, substitutes, and synthesis set a perspective for material availability over the next several decades. This is not a detailed projection for planning purposes. Rather, the point with respect to MSE is that with sufficient planning and effort we can have adequate resources for the foreseeable future. In order to accomplish this, substitution at several levels will be required. This is precisely where MSE will play a central role. First, one material can be directly substituted for another. The example of substituting aluminum for copper is discussed in Appendix 3G of this chapter.

Secondly, one can substitute a different function for one which is limited by scarce materials. An example is the use of microwave links to avoid long runs of copper-containing cable. At the third level, substitution may take the form of an entire new technology such as generation of electrical power by nuclear reactors to supersede oil-and coal-fired generators. In many cases, the development of adequate substitutes will require synthesis of new materials, which is precisely the arena where MSE plays a central role.

Materials for Housing and Urban Renewal

In the section on “materials for housing and urban renewal” in the next chapter, the point is made that while materials development can make important contributions to this national goal, the principal roadblocks lie in the nature of the industry, the inertia of building codes, and the requirements for long-life performance. Perhaps, MSE can have the greatest leverage on material development for housing construction through the creation of a material review board of truly national scope and prestige which could provide a critical and impartial evaluation of new materials sufficient to establish confidence in the minds of the architect, the builder, and the customer. Without doubt, science and engineering must couple closely to develop a knowledge-base on which to predict material performance for periods as long as 50 years. MSE can also make a significant contribution by helping to provide scientifically-based fire standards and fire-testing procedures for materials of construction.

Environmental Quality

Environmental quality is a goal toward which MSE should play a pivotal role. Although much can be accomplished by better exploitations of known engineering practices, ultimately a much larger science-base will be required for the optimal control of environmental quality. Purposeful coupling of science and engineering in MSE can effectively aid in the solution of a number of major problems such as pollution, recycling, manufacturing-process efficiency, and instrumentation to measure environmental degradation.

Materials Science and Engineering in Medicine and Biology

With a few important exceptions, the medical profession has done what it could on implanted prostheses using materials which had been evolved for other purposes. Recent development of new materials accomplished by close cooperation between materials specialists and medical practitioners has dramatized the progress which can be made in this field. Such instances afford excellent illustrations of the interdisciplinary nature of this activity, the need for additional scientific understanding, and the opportunities for new modes of interaction between the materials community and medical science.

Energy

Energy is one of the foundations of society. Attention has been focussed recently on the production of electrical energy, highlighting the conflict between rapidly expanding demand on the one hand, and on the other, growing concern about the undesirable by-products of electrical generation. Resolution of this conflict can be achieved by several routes. Nuclear-breeder reactors can eliminate the undesirable air pollution of fossil fuels, and produce more nuclear fuel. Significant improvement in turbine materials leading to higher operating temperatures can significantly shift the desirable-undesirable ratio in a central power plant. Magnetohydrodynamics (MHD) offers the possibility of converting heat directly to electricity at high efficiency. Solid-state electrolyte batteries may provide a virtually pollution-free energy source for some mobile applications. New superconducting materials can raise the efficiency in power generation and reduce losses in distribution. Each of these desired improvements in the generation of electrical power depend critically on materials development of the type which has been successfully handled by the interdisciplinary MSE approach.

This brief list of societal goals is in no sense complete, but it is sufficient to demonstrate that major national goals can be readily identified for which MSE must respond in vital ways.

Diffusion of Materials Science and Engineering into Low-Technology Indus tries

Coupling from an established field to an emerging activity is an important facet of MSE. Wood products serve as a good example. Until recently, structural wood was kiln-dried, inspected by visual criteria, and utilized with large safety factors to offset the wide variation from board to board. The concepts of solid-state science and engineering are now being reviewed for application to the problem. One of the newest developments to improve the engineering properties of wood is a special application of nondestructive testing (NDT). Whereas NDT is usually applied to other materials in order to detect unwanted inclusions or discontinuities, in wood it is being adopted to measure physical properties. For this purpose, various mechanical and electronic devices are employed to measure deflections and loads, or to monitor vibrations, in order to determine the modulus of elasticity. From such testing, other strength properties such as modulus of rupture are estimated through correlative procedures. Thus, the stronger pieces can be identified, and although the properties have not been modified in any way, the engineer can now select a superior material to design more efficient load-carrying structures. Overtones of effective conservation are evident in the practice of NDT methods.

However, it has been found that correlative procedures for estimated strength properties from modulus of elasticity are not sufficiently precise for some critical engineering applications, such as for the chord members of trusses, or the bottom members of laminated beams. Hence, there is continuing effort to improve NDT techniques. One possibility in this direction is based on the theory that energy dissipation or internal friction may be related to the same mechanism that controls strength properties. Wood is a mass of discontinuities at all levels of observation, and so it seems reasonable to assume that the theory has validity as well as feasibility in relation to wood. Studies thusfar in various wood research laboratories have led to conflicting conclusions regarding the possible utility of this approach.

At the moment, this research on internal friction deals primarily with electronic instrumentation in an effort to improve the precision of measurement of vibrational decay parameters. However, it will also be necessary to determine the relationships between these parameters and specific discontinuities as they further relate to strength properties. Fundamental studies in this field involve fracture mechanics, stress-wave theory, mathematical modelling, physics, and basic wood structure.

MATERIALS SCIENCE AND ENGINEERING AND THE BROADER SCENE

In the final analysis, MSE may fail even though it is properly organized as an interdisciplinary team and staffed with individuals of proper training and experience. Difficulty may well arise in the acceptance of new materials. Such obstacles may be due to human qualities, such as habit or inertia, or to organizational barriers which impede change and progress. In emerging programs, where there is generally high enthusiasm to develop something new, the requirement for materials development is more often recognized, and materials contributions are accepted because the success of the program is seen to demand their acceptance.

In mature industries, however, the situation may be quite different. Long-known materials and processes are familiar and comfortable; new materials may seem threatening and introduce unknown technical risks. In industries where the material itself is directly observable by the customer, there is also much reluctance to accept different materials. The shoddy ersatz materials necessitated by World War II shortages sensitized the public adversely to material substitutes. Fortunately, the outstanding successes of a wide variety of plastic materials with superior characteristics have offset this suspicion to the extent that many products are now quickly accepted, industry-wide self-discipline with regard to releasing new materials should also help eliminate this long-standing public prejudice against substitute materials.

Until now, MSE has contributed to national welfare mainly by technical proficiency. It is time to recognize that the role of MSE in new national goals will require more than elegant solutions of technical problems. Also important are related factors in the realm of social science due to problems arising from long-held customs, threat of change, building confidence in something new, and communication of semitechnical information to the public. Thus, MSE must learn how to join forces with social research in order to meet its larger objectives. Some effort along these lines has been started in governmental laboratories and industrial concerns, but the university would appear to be an ideal location for this type of broad interdisciplinary activity.

CASE STUDIES OF MATERIALS SCIENCE AND ENGINEERING

APPENDIX 3A Heatshield Design Problems

Introduction

The primary purpose of the heatshield in any reentry system is to provide thermal protection from the reentry environment and thereby allow successful completion of the intended mission. From the first definition of heatshield requirements to synthesis of a system to meet these requirements, support in the areas of orbital mechanics, aerodynamics, trajectory analysis, heat transfer, physics, chemistry, material science, experimental testing, and manufacturing techniques is essential. The hostile environments generated as a result of reentry are dependent upon the mission, vehicles design, and payload. These three considerations form the basis for trajectory selection, vehicle performance (ballistic coefficient) and payload tolerance level, and, therefore, to a large extent define the range of expected reentry environmental parameters. Obviously, the applications can be widespread—from the safe return of man from planetary or earth orbital missions to severe reentry of Intercontinental Ballistic Missiles. The range of resultant reentry parameters is so extreme that design of one vehicle to be optimum for all applications is not feasible. In fact, vehicle design, depending upon the mission, could be predicated on deceleration level, temperature, material response, thermal stress, or combinations of these. The design problem is relieved somewhat by the availability of materials, design concepts, and calculational procedures which have evolved most noticeably over the past 10 to 15 years, We describe briefly the environments and resultant heatshield or thermal-protection system design problems related to manned earth orbital or lunar return reentry (APOLLO) and unmanned planetary return (SNAP-RADIOISOTOPIC HEAT SOURCE).

Reentry Environments

Perhaps the single most important parameter which determines the reentry environment is the vehicle ballistic coefficient or weight-to-drag area ratio (W/C_DA). Examination of simplified equations of motion shows functional relationships between the ballistic coefficient and velocity, altitude of maximum deceleration, altitude of maximum heating rate, and maximum heating rate. For a fixed reentry velocity and angle, an increase in ballistic coefficient produces higher heating rates and increased total integrated heat. The value of maximum deceleration is not strongly dependent on ballistic coefficient, but rather depends on reentry velocity and angle, with increases in velocity and angle yielding an increase in deceleration loads. It is apparent that selection of a low ballistic-coefficient vehicle leads to a reduction in the overall thermal environment to be experienced. The magnitude of vehicle “local” thermal environments is further influenced by vehicle size and configurations and will be discussed later. The major reentry environmental parameters for vehicles entering the earth’s atmosphere are the convective heating rate, total heat-load or integrated convective heating rate, total pressure, and vehicle deceleration. Representative values of these parameters for several systems are shown in Table 3.4. It is these parameters which set the heatshield design and material property requirements.

Early Development

Early in 1960, studies for a manned lunar mission were initiated by the Space Task Group of NASA; Space Nuclear Auxiliary Power (SNAP) devices then envisioned employed the burn-up concept so that intact reentry was not a requirement. Most aspects of the thermal environment were reasonably well established by the techniques available at that time. It was recognized in the Apollo program that a relatively blunt vehicle would be required to minimize convective heating, but some concern was expressed over the magnitude of nonequilibrium radiation from the shock layer to the body. Estimates made in this time period indicated that nonequilibrium radiation might be orders of magnitude higher than equilibrium radiation and might be a dominant factor in entry heating. Further theoretical studies and experimental work conducted in shock tubes and light gas guns dispelled this concern and showed that for the Apollo application the command module configuration should be designed to provide minimum convective heating. However, lunar ballistic reentry allowed entry in a narrow corridor seven miles wide. In order to widen the corridor, a moderately lifting vehicle (L/D=0.3 to 0.5) was suggested, and undershoot trajectories limited to 20 g’s for crew survival and overshoot trajectories (5000 nm range) for maximum heat load were studied. Therefore, the manned lunar mission, entry corridor, convective heating and deceleration limits defined the major design requirements for reentry of the Apollo command module.

By the mid 1960’s, studies had shown that the previously used burn-up philosophy during reentry of SNAP devices was unsafe in that a potential existed for dispersing radioactive material in the earth’s atmosphere. It was decided at this time to convert the fuel capsule in the Nimbus-B/SNAP–19 generator system from a metallic burn-up capsule to a graphite-heatshield protected system to provide intact reentry. The concept of the omnidirectional vehicle with graphite external heat shield was adopted and applied to heat sources in the Apollo (SNAP–27) Transit (Navy satellite), and Pioneer (Jupiter Fly-By) programs. The design requirements for these systems were extremely broad since manned reentry was no longer a consideration and mission applications ranged from earth orbital decay to extreme planetary return reentries. In addition to very large total heat loads (42,000 BTU/ft^2), high heating rates and severe thermal-stress problems arose from high-velocity, high-angle planetary returns. These problems were further complicated by the fact that internal heat generation by radioisotopic fuel decay was inherent in the vehicle. This led to a heatshield design requirement to provide adequate ablation performance, thermal-stress resistance, protection of internal components for entry and impact, and to provide the necessarily fine

TABLE 3.4 Typical Reentry Environment Parameters for Reentry Vehicles Entering the Earth's Atmosphere

Mission	Reference Heating Rate, $\dot{q}_{Ref_{max}} \frac{BTU}{FT3/2\ sec}$	Total Integrated Heat, $\int \dot{q}_{Ref} \frac{BTU}{FT3/2}$	Vehicle Maximum Pressure, P_{T_2} (atm)	Vehicle Maximum Deceleration (g)
SNAP 27 Preorbital	300	8,500	1.4	25.0
SNAP 27 Earth Orbital	100	42,000	0.17	7.0
SNAP 27 Lunar Return (6.25°)	500	25,000	0.37	14.0
SNAP 27 Lunar Return (38°)	1,600	9,000	5.4	200.0
Pioneer Jupiter Return (9°)	1,500	40,500	2.0	45.0
Apollo (Entry Design Limits)	700	42,000	1.5	20.0

thermal balance for acceptable steady-state operational temperatures for internal components. These problems were moderately relieved by the fact that generally blunt, low ballistic-coefficient vehicles were allowed in the weight and space specifications for the devices.

Heatshield-Material Selection and Design Concepts

Early wind tunnel data in the Apollo program on the command-module heating distribution showed that a reradiative protection approach was theoretically possible on a large area of the conical region. Uncertainties in the level of heating in flow attachment regions and the indeterminate problems of an ablator-radiator juncture, however, led to the choice of an all-ablative system. Many thermal protection materials were undergoing tests during the preliminary design phase in 1960 and 1961. The Mercury heatshield material, a high density (110 1b/ft^3) glass phenolic, was considered but dismissed because its high conductivity was ill-suited to a long entry. Nylon-reinforced phenolic (75 1b/ft^3) was studied by the NASA Langley Research Center. When described in terms of “effective heat of ablation,” the material looked promising but would result in a thermal-protection system weight of 2900 1bs. During the winter and spring of 1960–61, several materials were considered by aerospace contractors for the lunar return mission. These included phenolic nylon, epoxy ablators, and Avcoat 5026–22 epoxy-novalac, a silica fiber reinforced material. Phenolic nylon tiles over a supporting honeycomb-sandwich structure of stainless steel was the approach finally selected. The main design requirements for the ablator were that it limit the temperature at the ablator-steel interface to 600° F during entry, that it be compatible with the steel substructure, and that it survive thermal cycling from -250° F to +250° F prior to entry. In addition, it was required to provide boost thermal protection and to withstand micrometeoroid, vacuum, and ultraviolet exposure.

By contrast, the materials chosen for the isotopic heat source were required to have high steady-state surface temperature capabilities (900° F), resistance to high heating rates, and the capability to limit the thermal input to the vehicle during entry. These properties were exhibited by the POCO and ATJ-S bulk graphites. In addition, the bulk graphites displayed acceptable ablation rates (thermochemical) and thermal stress resistance over the range of pressure, temperature, and enthalpy experienced.

Supporting Analytical Program

Early methods used to predict the required ablator thickness at each point on the body of the CM used a recession correlation based on effective heat of ablation coupled to a solid-state conduction analysis. Attempts to study special regions, such as protuberances, suggested that wholly rational treatment of singular regions was not possible. The requirement for a safe design coupled with available analytical techniques led to conservatism, undefined margins of safety, and in some cases undesirable weight penalties. While the heat of ablation approach, expressed as a function of environmental energy, surface temperature, and heating rate, was considered fast and convenient for design, a more complex analysis was required to verify final heat shield designs. More elaborate approaches have now been developed which involve a complete energy balance at the surface and an accurate treatment of the characteristics in systems employing charring ablators.

Supporting Materials Program

It is evident from the previous description of the reentry environment and heatshield design problems that synthesis of materials tailored to meet the design requirements was essential. This role was fulfilled by MSE. The specific contribution of the materials professional within the ablation heat-shield development team might be exemplified by a brief description of the general process of materials selection and the tools which are used. In general, the materials specialist is involved in the physical phenomena and chemical interactions between the reentry environment and an ablative material. Current ablation theory states that an ablation material can reject heat in the following ways:

(a) by warming from some temperature to the decomposition point and above (high C_p);
(b) by decomposing into small fragments (high decomposition energy);
(c) by tailoring the fragments to have high specific heats in order to carry off a large amount of heat; and
(d) by forming an outside layer of porous char which reradiates some of the heat energy away and which adds additional heat to the gaseous fragments which perculate through it.

In addition to these heat-rejection mechanisms, the ablator performs the function of insulating the interior of the vehicle from the high-temperature surface. Depending upon the reentry environment and proposed application, the materials engineer, whose role is to assess the practicality of tailoring a material to fit a set of desired attributes, will select one or more of the four ablation mechanisms to be the predominant method of heat removal.

In order to make the first cut choice of an ablator, the materials man uses expertise from several disciplines: organic and physical chemistry, physics, mechanics, and polymer chemistry. An example will illustrate the process more fully.

Assume that the guidance from the other part of the team indicated that the material must, as one of several requirements, have a high decomposition energy. The materials expert would then begin to optimize materials for each part of the requirement, after which he would run a series of parametric studies to obtain an ablator.

To address the requirement of high decomposition energy, chemical theory would first direct him to the most thermally stable organic molecules, as follows: Chemical-bond thermodynamics shows that in organics p bonds are stronger than s bonds (142 versus 80 kcal/mole). In addition, the theory of quantum—mechanical resonance of conjugated p bonds indicates that additional stability can be obtained by delocalization of as many p bonding electrons as possible. This results in the selection of aromatic hydrocarbons as near to the structure of graphite as possible.

The next step is to incorporate this molecular structure in a usable material. Since graphite is not a workable material, other smaller aromatic molecules are considered (benzene, toluene, biphenyl, phenol, etc.). These molecules alone are of no value; therefore, they must be made into a usable solid, a polymer. Chemical-bond thermodynamics and resonance theory again provide the direction for the kind of joining required, all p bonds. However, polymer structure-property relationships indicate that an aromatic polymer will not be usable when the aromatic rings are joined by p bonds. Trade-off studies have shown that the best system would be to use a carbon-to-carboh bonds with as few as possible in the joining link and hace as many joining links as possible.

At this point, a decision must be made as to the kind of polymer desired, a thermoplastic, a rubber, or a thermoset material. Polymer thermal-decomposition studies show that, in general, the higher the crosslinking, the more thermally stable. Also, from mechanical considerations of heatshield strength a crosslinked material is required. When these considerations are combined with a knowledge of organic reactions, a reaction is selected which will allow a first-cut material to be made. This reaction is a condensation reaction of formaldehyde with phenol (phenolic polymer) to yield an aromatic structure joined together by two a carbon-carbon bonds in each link. In addition, since phenol has a possibility of three reaction sites, two ortho and one para to the hydroxyl, the degree of crosslinking can be varied to suit the requirements.

Condensation reactions usually yield by-products, small molecules which are removed in gaseous form. When large test samples are required, the diffusion times for these gases to be swept from the system become prohibitively long. If heat and pressure are used to speed the diffusion and condensation reaction, large material defects, bubbles and voids, will always occur. A compromise which allows the preparation of good samples in spite of the offgassing is obtained from the knowledge that, first, some polymerization reactions can be carried part way to completion, stopped, and then restarted. This allows the removal of an appreciable amount of the gas before sample synthesis is attempted. Parametric studies are done to optimize the amount of prereaction. Second, diffusion studies have shown that gaseous diffusion is several orders of magnitude larger along polymer interfaces than through a bulk polymer. Thus, any filler which would give a continuous interface would enhance the removal of the gas. With this expertise, blocks of material can be made for testing.

In the manner just described, also addressed in the MSE mode are: fiber technology, char technology, layup technology, ablation-reaction chemistry, adhesion, physics of transpiration cooling, all to optimize each desired attribute. Then parametric studies are used to distill the mixture of best attributes into one best ablator for a given application.

Thermal properties, including calorimetry for specific heat and enthalpy, are needed to determine the amount of energy required to warm the material to the decomposition point. Thermal conductivity of the virgin material and the char is needed to indicate the velocity of the heating front. Thermal expansion and thermal shock resistance are required to determine compatibility with the substructure as well as the structural integrity of the virgin ablator and the char during the service conditions.

Mechanical properties include static and dynamic loading at elevated temperatures on both the virgin material and the char. These data allow stress analysis in order to make predictions of the performance of the heat-shield during flight and other loadings. In addition, early in the study, certain of the mechanical tests would be used as screening methods to determine which of several fibers (e.g., carbon, quartz, or nylon), available through previous research, would be the best choice in this application. Several generations of material are required to optimize and trade-off the requirements of all members of the design team.

Both preliminary ablation testing to help screen candidate composite formulations by visual postmortem, material loss and energy absorbed/unit material, and final proof testing with conditions as near those of the flight as possible must be made. The final shield or test article should be instrumented with heat, material removal, char depth, etc., sensors to show final acceptance (usually in concert with a heat [energy] transport team member).

The synthesis of prototypes and actual heatshields would be the next requirement of the materials man. He must include in his considerations such things as, how should any reinforcing fibers or cloth matrix be used to produce the correct mechanical properties? How should the material be configured? How should the ablation shield be attached to the substructure? Has the weight allotment been met? Can better physical geometries be found through parametric computer studies? Can the shield be made more reliable by computer control of the fabrication equipment?

To consummate the discussion, one must remember that as the solutions to most problems are never black or white, neither is the choice of ablator without its trade-offs. To obtain a very necessary property, such as low back-surface temperature, other properties, such as char formation, will degrade. These trade-off studies, along with testing, theories of ablation, decomposition, polymer synthesis, composite synthesis (mechanical properties), are also functions of MSE.

Material characterization is carried out with laboratory samples sufficiently large to measure chemical and physical properties, bearing in mind that, as an example, the mechanical characteristics of a reinforced polymeric system can be significantly affected by its geometry. Thermogravimetric and differential thermal analyses, as well as gas chromatography and mass spectrometry, are used to determine the decomposition energy, the amount of char and the gaseous species formed during ablation. These tests will also show the compatibility between the organic and the fiber and substructure. At this point, additional molecular tailoring may be done to further enhance a property. An aid is the use of microscopy and x-ray diffraction to identify structure and structural changes of both the virgin material and the subsequent char.

The importance of MSE in the heatshield design area is further exemplified when one considers the serious problem of variability of material properties in materials supplied by commercial vendors. Vehicle design considerations and safety factors based on minimum material properties lead to conservative design, a luxury which may not be tolerated in extreme reentry environments. As reentry environments become more severe, it is through the work of MSE under controlled labroatory conditions that new materials will be created to satisfy the demand for ever-increasing performance of ablative heat shield materials.

APPENDIX 3B

Discovery of the Transistor

One of the best-known examples of multidisciplinary and interdisciplinary R & D is that which led to the discovery of the transistor and the subsequent creation of a whole new technology.

The transistor was discovered in the Bell Telephone Laboratories. As expressed in its corporate goal, the Bell Telephone System has the obligation of meeting one of the major needs of society, namely, “To provide the best communications service at the lowest possible cost consistent with financial health.” This goal must be met in ways which enable the Bell System to compete with other industries for the necessary capital and other financing. Thus, Bell Telephone Laboratories is an R & D organization coupled to an industry required to meet a social need in a financially (competitive) efficient manner. From the management point-of-view, this immediately translates into having continually to find ways of improving the technology of communications. In this way the Bell System can meet the external pressures of social demands for better (i.e., more diverse and reliable, cheaper, quicker, etc.) communications and the internal corporate pressures for competing in the market (i.e. , lowering costs, installing equipment more quickly, higher reliability, etc.)

So, in the mid 1930’s, Mervin Kelly, then Executive Vice President of BTL, found himself wondering about the limitations of relay and electron-tube technologies. It was his job to look ahead 10 to 15 years. He reasoned that if one had to rely only on tube or relay improvements, the Bell System would not be able to afford the larger, more complex, and more capable communications systems that would be needed in the future. There were simply too many intrinsic physical limitations in both electron-tube and relay technologies. Relays were low in cost and reliable, but far too slow to perform the more challenging functions of the new switching systems needed. They could work for digital functions, such as low-speed logic and memory, but could not be applied to the many other analogue and high-speed digital functions that a complete future communications system would require. On the other hand, electron tubes were very fast. All they had to do was move electrons in vacuum in response to information signals. They could perform both high-speed digital and analogue functions. But electron tubes extracted a large economic penalty. The hot cathode consumed power in wasteful quantities and the failure rates of tubes were too high to allow the use of large numbers of tubes per system. Thus, operating costs and maintenance expense would prohibit the applications of electron tubes to the much larger, more complex switching and multichannel transmission systems that were needed. And, of course, tubes were absolutely ruled out of telephone apparatus by their short comings on power and reliability as well as size. So Kelly concluded that a new component technology was needed. It must be fast and versatile like the tube, but it must be efficient in its use of power. Above all, it must be many orders of magnitude more reliable than tubes it it were to be applied to the much larger, more complex systems of the future.

The outbreak of World War II made it necessary to shelve plans to follow this train of thought with action; but after the war, Kelly returned to the problem. When he told his research people what concerned him, they told him of the current state of understanding in many relevant areas of physical electronics such as cold-cathode gas-discharge phenomena, magnetics, electroluminescence, and conduction of electricity in such solids as metals, insulators, and semiconductors. One by one, most of the possibilities were eliminated because of one limitation or another; insufficient speed, too many restrictions in functions, or the judgment that sufficient understanding to achieve application could not be developed soon enough. The search narrowed down to solids, such as insulators, metals, or semiconductors. In a conductor there are many electrons, but not enough of the basic science was known to control them. In an insulator, there are very few electrons and not much to be done about it without altering the basic material structure. But in a semiconductor, there can be many electrons or not, depending upon what one does to the semiconductor with impurities, heat, light, or electric stimuli. For many years, empirically-discovered semiconductor devices had been used in electrical technology, such as copper oxide and silicon rectifiers, and resistors whose characteristics could be controlled in response to thermal, light, and electric signals. Researchers were trying to understand why a semiconductor behaves as it does. How does it differ from metals and insulators? Why is its resistance so sensitive to impurities, imperfections, and various forms of energy? Wilson and Mott had studied these problems in England; Davidoff and Joffe in Russia; Schottky in Germany; Lark-Horowitz at Purdue University; just as people had done at Bell Laboratories. There was indeed a large and impressive body of theoretical and experimental work at hand. Shockley and Fisk concluded that the most promising and relevant area in which one might look for new electronic phenomena for amplification lay in semiconductors—if one could understand the basic physical and material science.

The best theory in those early days did not explain the relation between structure and function in any quantitative way for copper oxide or germanium rectifiers. In fact, it would not even predict accurately the direction of rectification. But certain promising things and aims were known: It was known that the need was to produce and control the flow of electrons such that the basic atomic structure of matter would not be altered; otherwise the same kind of wear-out problem would result as with hot cathodes. It was known there could be many electrons in semiconductors at room temperature, and that they could be moved very fast without altering the basic material structure. For example, silicon and germanium rectifiers would behave as very fast electronic switches, and other similar devices would also respond to heat- and light-signal energy. So the real question became: Can we understand, and thereby learn how to economically generate and control, the electrons in semiconductors? The decision to do research on semiconductors was finally made; it was signaled by Kelly, but only Fisk, Shockley, and their fellow researchers knew the scientific potential. Together, managers and scientists formed a synapse between a broad long-term system need and a possible answer in a relevant area of science. They had no concrete ideas on what form any new electronic device might take, but they had faith that basic understanding of semiconductors could lead to the snythesis of a new electronic device.

Nobody could put a quantitative value on the probability of success or on how long it would take to succeed. All that could be said was that there was an excellent chance of achieving understanding because the quantum physics of solids was mature and powerful; at least, understanding of the simplest elemental semiconductor, such as germanium, should result. This was why work started with germanium and later turned to silicon, despite the fact that more complex semiconductors, such as copper oxide and silicon carbide, were in much larger commercial use as empirically developed devices. The simplest material was picked because basic understanding was being sought which, it was hoped, would in turn lead to control and use based on such understanding.

The Research that Led to the Transistor

The decision to intensify research into semiconductors, which were originally discovered by Faraday in 1833, reflected awareness of the intriguing variety of properties of these materials that had been discovered in the preceding hundred years as well as their use already in a number of rudimentary devices. These basic discoveries and the development of a formal understanding of them were very much the inspired work of individuals whom we would nowadays call solid-state physicists—for example;

1839–	Becquerel discovers photovoltage between semiconductor and electrolyte. 1873–Smith discovers photoconductivity in selenium.
1874–	Braun discovers non-ohmic behavior at metal-sulfide contacts.
–	Schuster discovers non-ohmic behavior at copper-tarnished copper contacts.
1876–	Adams and Day make barrier-layer photoelement with selenium.
1879–	Hall effect discovered, indicating some metals have positive carriers.
1883–	Fritts makes first large-area dry rectifier with selenium.
1904–	Various discoveries that point contacts on galena, silicon carbide, tellurium, and silicon make good detectors of radio waves. (Silicon was found to be the most stable and though the rectification mechanism was not known, it was shown not to be thermal.)

We see from the above list that some basic properties of semiconductors and particularly the rectifying properties of contacts were established as far back as 1883. By 1904 it had been shown that such contacts could be used for detecting radio waves but the suitability of vacuum tubes at that time for such applications lessened or delayed interest in semiconductor effects.

However, in the 1920's, various commercial semiconductor devices started making their appearance including the copper oxide and selenium rectifiers and selenium photocells. These commercial devices created a demand for a better understanding of how they worked, so that through the 1920's and 30's much experimental research went into the properties of semiconductors. Some of the best controlled studies were made in Germany by Gudden and Pohl on the related materials, (generally more insulators than semiconductors) alkali halides; their progress, it was clear, was considerably aided by the fact that such materials could be prepared fairly readily in single-crystal form. As a result of such researches, it was established that rectification and photovoltages were contact or surface properties; conductivity and photoconductivity were body properties. In the meantime, theoretical physicists were beginning to invoke conceptual models for the energy states and electronic properties of solids. In 1928 Sommerfeld developed a better understanding of conduction in metals, and in 1931 Wilson published his famous work which established the energy band model and the role of valence, conduction and forbidden energy bands. These advances, of course, were very much based on the new concepts of quantum theory, statistical mechanics, and the Schrödinger equation which had been introduced in the 1920's and were now finding a wide range of applications in the physical world.

Based on the Wilson model of semiconductors, a number of their body properties became more readily understood, such as the temperature dependence of conductivity, conduction and photoconduction, and in the later 30's the roles of donor and acceptor impurities electrons and positive holes, and the chemical picture (based on bonding) of electrons being ionized from bands into the freely conducting state. A conceptual blind-spot that persisted for some years was a realization of the important role of minority carriers. Progress was less rapid with the surface properties. Good rectifiers seemed more an art than a science. Experimentally, correlation was established between the direction and rectification and the sign of the majority carrier of the semiconductor but early theories (by Mott, Schottky, Davydov) predicted the wrong direction of rectification. It turned out later this was because the role of minority carriers was overlooked.

As research into the properties of semiconductors progressed, it was realized more and more how vital was the ability to control the composition and structure of the materials. Chemists and metallurgists were appealed to for help in getting purer silicon and later (after recognizing how n- or p-type, rectification direction, and accidental p-n junctions correlated with impurity segregation) controlled amounts of identified impurities which led to control over the n- or p-type nature of a semiconductor. Such was the state-of-the-art when World War II struck. Based on this art, nevertheless, many important semiconductor devices were produced, notably for microwave detectors in radar. When the War ended, following Kelly's urging outlined earlier, researchers at Bell Laboratories resumed the attack on semiconductors. They had the intuitive feeling that if only they understood semiconductors better and had more control over the material, important new electronic devices, particularly amplifiers, would be forthcoming. Specifically, Shockley believed that it should be possible to modulate the resistance of a thin layer of semiconductor by imposing a strong electric field gradient across the layer and quickly controllably changing the number of available carriers of current. It was obvious that electronic amplification could be based on this effect if it existed. Thus, several physicists, chemists, metallurgists, and electrical engineers started working together in the interdisciplinary MSE mode. The years 1945–1948 saw much experimentation, the posing of phenomenological models, the failure to confirm the model with experiment, the devising of new models, predictions of certain effects which experiment failed to confirm, and so on—a familiar scenario to researchers striving towards a deep understanding of nature. New concepts had to be proposed to replace the old ones that had failed. An important one was Bardeen's theory of surface states, which was introduced in order to explain the failure to observe the large field effects in solid-state triode structures that Shockley had expected. This idea led to a realization of the importance of minority carriers in the behavior of contacts. And in 1948, the point contact transistor was discovered by Bardeen and Brattain. It is clear that these unanticipated, important, and radically new results emerged from the steady pursuit of exact science with a purposeful goal, and not simply from the elaboration of known technology.

Once the role of minority carriers had been understood, Shockley quickly followed with the prediction of the junction transistor, both p-n-p and n-p-n. The potential performance of such junction devices appeared more promising than that of the point-contact transistor, particularly for its stability and its power handling capacity. But to realize such a structure, called for even better control over material preparation. From this point on, it is perhaps fair to say that, though physicists and electrical engineers continued to have many of the device ideas, the pace of progress in semiconductor R & D was determined very much by the progress of the chemists and metallurgists. Absolutely vital steps were the discovery of zone refining by Pfann and the development of ways to grow high-quality single crystals of germanium and silicon. As a result, the grown junction transistor was demonstrated in 1951.

New methods of preparing junctions and transistors with improved performance followed quickly, first alloying, then diffusion processes. New devices and applications were not far behind, including silicon power rectifiers and solar "batteries." The family of useful semiconductors was extended in 1953 by Welker working at Siemens in Germany, who showed that a range of binary compounds based on the group 3 and group 5 columns of the periodic table were analogs of the group 4 elements, silicon and germanium. These new compounds were eventually to lead to whole new classes of important semiconductor devices.

The materials work, directed towards improving the technology of semiconductor devices, proved a rich source of new fundamental understanding of materials. Important spin-offs were better control over doping, the identification of impurities, new techniques for growing crystals, deeper understanding of solid-state solution theory and crystal-growth kinetics, thermodynamic theory, and by no means least, the nature and consequences of dislocations. The last topic, for which solid-state research laid much of the groundwork, was to have far-reaching influences in other areas of MSE.

And so solid-state electronics was born.

APPENDIX 3C

The Development of Coated Stainless Razor Blades

In the decade beginning with the year 1945, an interdisciplinary group of scientists and engineers at the Gillette Company began a long-range study of the properties and uses of razors and razor blades. This group comprised chemists (polymer, organic, and physical), metallurgists, physicists as well as mechanical and electronic engineers. The work of this MSE group set the stage for a series of discoveries for improving shaving, which is continuing to this day. Fundamental studies of razor-blade edge geometry and metallurgy were undertaken using electron microscopy which was a new tool at that time.

After considerable difficulty, techniques were devised to study razor blade edges with the electron microscope. This new tool showed that the heretofore unresolved edge dimension was a few hundred angstrom units on mass-produced razor blades. For the first time, it was possible to demonstrate that the mechanism of failure in service was different for high-carbon steel blades than for stainless steel blades. These studies also showed that the carbon steel blades were being chemically eroded during shaving. This led to a program to reduce the deterioration of carbon steel edges during shaving. One of the means explored to accomplish this end was to coat the carbon-steel edges with metal coatings. Most of these were applied by vacuum evaporation of the metal onto the edges. Because of the very small ultimate edge dimension of the blade, these coatings were kept very thin, no more than a few hundred angstroms at the most. Improved shaving life of carbon steel blades resulted with some sacrifice in initial shaving quality.

While this work was proceeding, one of those side experiments, so common in research, was performed. This experiment was to test whether a high molecular—weight polymer could be transferred across a vacuum onto a metal surface to form a continuous coating. PTFE was chosen as the polymer for the test because of its extremely high heat stability. The transfer was conducted onto razor blade edges (rather than on the articles then of primary interest) solely because razor blades were the most convenient objects available to be used in the particular apparatus employed. The PTFE was heated in an incandescent tungsten coil until an increase in pressure in the vacuum chamber was observed. The razor blade edges were examined after deposition by light microscopy. Wetting tests showed that some PTFE had, indeed, transferred across the vacuum chamger. Further tests showed that contrary to expectations, the cutting ability of razor blades had been improved by the PTFE coating. Subsequent shaving with these blades showed an improvement, beyond that normally obtainable with uncoated blades.

This was the first time a razor blade had been obtained with a shaving quality above and beyond that obtainable by normal sharpening practice and despite the fact that a rather thick coating had been bonded to the ultimate edge of the sharpened blade.

This discovery led, in due course, to an exhaustive study of fluorocarbons for coating razor blade edges. It was clear from the initial experiment that degradation of the high molecular-weight PTFE had taken place and that a lower molecular-weight material had actually been deposited onto the blade edges. Studies of the “evaporated” PTFE showed it to have a lower melting point and higher crystallinity than the starting material.

Attempts were made by the group to synthesize fluorocarbons of carefully controlled molecular weights. Great difficulty was encountered in this work and soon help was sought outside the company from a large chemical manufacturer expert in this field. A major problem with commercially available high molecular-weight PTFE was the particle size combined with the very high melt viscosity. These polymer particles, when heated well above their melting point, failed to flow and coalesce into a pore-free film. Although the particles did sinter to form an adherent bonded film on the blade edge, adequate surface coverage required several layers of particles in the film. Since virtually no flow of the particles took place during sintering, the resulting PTFE film thickness was in the order of a micron or more. This film thickness was detrimental to initial shaving quality and as a result, a "break-in" period of several shaves was required as the film wore thinner before optimum shaving quality was realized.

To avoid this loss of initial shaving quality, a PTFE-type polymer with a melt viscosity in which the melted particles would flow freely and coalesce during sintering was sought. PTFE-type polymers and telomers with molecular weights ranging from as low as a thousand to as high as several million were made. The very low-molecular weight PTFE, while flowing freely, failed with respect to shaving life of the film on blades. Intermediate molecular-weight material from about 30,000 to 200,000 exhibited the desired melt-flow properties for film formation and, surprisingly, produced blades of shaving life exceeding that of the very high molecular-weight commercial PTFE polymers. PTFE-type polymers in this molecular-weight range could produce much thinner pore-free films (of the order of one-to two-tenths of a micron) which showed excellent shaving quality from the very first shave.

The result of the better flow properties of these polymers was easier film-thickness control in mass production.

Concurrently with the work on synthesizing new fluorocarbon polymers, studies were made of high molecular-weight PTFE and its behavior when heated on different metallic surfaces in a variety of gases. This work showed that there was an interaction between the PTFE, the metal, and the gas to produce a variety of different PTFE coatings under the same heating conditions.

Studies of PTFE-coated blades were made after various stages of shaving. It was possible to show that the PTFE coating persisted around the ultimate edge of the blade for several shaves. The PTFE coatings were removed from the blade edge after shaving by dissolving the steel and floating off the coating, which could be shown to remain intact across the ultimate edge in many places.

More recent work on razor blades, where electron microscopy and physical metallurgy have played a predominant role, has been the development of edge-strengthening metallic alloy coatings. Studies of evaporated and sputtered metallic coatings for razor blade edges has led to the use of an ordered alloy of platinum and chromium. This alloy, with a superlattice of the intermetallic compound Cr_3Pt, when coated on razor blade edges and then overcoated with PTFE, provides blade edges of excellent shaving life. While it is easy to demonstrate the presence of the ordered superlattice structure of the Cr_3Pt alloy in bulk melted samples by conventional x-ray diffraction techniques, it is extremely difficult to show this in thin films on razor blade edges. However, a careful electron microscopic and electron diffraction analysis of alloy coatings, 300 to 500 Å thin, reveals that intermetallic compound with the characteristic A15 cubic ordered crystal structure does form in these vapor-deposited thin films. The grain size was shown to be extremely small, and the presence of some lattice defects was found within the fine grains. It was not possible to analyze the structure by any other technique. Under some circumstances, the line broadening due to small grain size and lattice defects was so great that the characteristic lines effectively overlapped, giving rise to a broad diffuse ring in the electron diffraction pattern.

The Cr_3Pt alloy exhibits a DPHN hardness in excess of 1400. This is far in excess of the normal hardness of PTFE-coated razor blades which range in hardness from 550 to 650 DPHN. X-ray diffraction techniques have made it possible to characterize the structure of the Cr_3Pt alloy in bulk, while the electron microscope has made that possible in thin films useful for razor blade edges.

APPENDIX 3D

Synthetic Fibers

Introduction

Textile materials have been developed over many hundreds of years and the most suitable natural fibers have provided the basis for today's textile industry. These natural (as opposed to synthetic) textile fibers are cotton, wool, flax, and silk, with silk giving the highest strength properties. Except that silk is spun by the silkworm, methods for the spinning and weaving of natural fibers have been accepted routines since before the Industrial Revolution.

Although still of great importance, natural fibers have given way to the science and engineering developments of regenerated (natural) fibers and more significantly to the developments of synthetic fibers. Synthetic fibers are those in which man has chemically synthesized the fiber-forming polymer-base material and engineered the operation of fiber production through the use of machines, in contrast to relying on either plant or animal life to do either of these jobs.

The development of the synthetic fiber industry as we know it today required intense interfacing of various MSE disciplines. An excellent example of this is the story of "nylon," a duPont polyamide fiber. Nylon emerged as a very important lightweight, high-strength fiber during WWII for making parachutes, rope, tire cord, etc., and subsequently for producing hosiery and other important textile materials. As is the case for all synthetic fibers, the fiber is spun from a polymer-base material synthesized from basic chemicals derived from coal, oil, etc. (materials science). Nylon fiber is obtained from the polymer-base material by melting it and squeezing it through tiny holes (spinning) into thin strands which are stretched like taffy into the filaments desired (materials engineering).

The way for the convergence of MSE to produce nylon was paved by the starting of a "pure research" program in 1928 aimed to obtain fundamental knowledge. DuPont history tells us that the initial purpose of the program was for future company diversification, but not oriented toward a specific product. It should be recognized, however, that the selection of Dr. Wallace H.Carothers (1896–1937) from the Harvard faculty, who was known to have intense interests in the field of polymer chemistry, to head up this research program is indication that the future importance of synthetic polymer science and engineering was foreseen.

The advancing materials science provided the capabilities for synthesizing the new high molecular-weight polymers required, and engineering disciplines provided the know-how for causing the macromolecular chains of these materials to align under the shear of extrusion through spinnerets. It was also learned that after extrusion the spun fiber could be further stretched to improve the molecular alignment of chains for improved strength and performance characteristics.

It is of interest to examine in more detail the MSE responsible for putting synthetic fibers into today's economy.

The Materials Science

Born in the twentieth century, polymer science is one of today's most important materials sciences. A polymer molecule is a giant molecule made up of many thousands or millions of simple molecules linked together into long chain-like structures (macromolecules). All natural fibers are made up of macromolecules, and the important mechanical properties of fibers are the result of interactions between the long chains. Long-chain molecules are lined up parallel to each other in fiber formation. The better this alignment is, the stronger are the interactions between polymer chains, and the higher is the tensile strength of the fiber.

In the late 1920's, there was an awareness of the importance of polymeric materials. Natural materials were known to be made of giant molecules or polymers and in particular the value of polymer materials such as wool, cotton, and man-made rayon were known. Also, early ground work in the field of polymer synthesis was being laid in a few laboratories, but no work had been successful at that time in synthesizing a polymer which could be made into a synthetic fiber with useful properties. When Dr. Carothers was brought in by duPont, he was encouraged to carry on fundamental research in organic chemistry of his own choosing. His interests were concerned with the synthesis of high polymers such as those found in nature, and in his new research position he chose to investigate polymerization by condensation as well as the structure of high molecular-weight substances. He commenced his research in the midst of other research groups in the laboratory and soon he had a group of chemists numbering about a dozen working under his personal supervision. These consisted principally of organic and physical chemists, the former to synthesize polymers and the latter to determine their properties.

The role of the research chemists and their discoveries cannot be overemphasized in discussing the origins of synthetic fibers. By synthesizing new polymeric materials unknown in nature, by recognizing their importance, and by synthesizing them in high enough molecular weights to be useful (in this case, for being converted to fibers with strengths to compete with silk), the organic chemists achieved great successes.

The chemical research led to synthetic procedures for polyamides, polyesters, polyanhydrides, and neoprene rubber—all synthetic polymers. The early research on polyesters opened the way to many important scientific observations. It was found that molten polymer could be drawn out into threads using a glass rod. It was further found that these threads could be pulled (cold-drawn) to several times the original length of the thread and that the resulting drawn filament would exhibit much higher tensile strength than the undrawn filament. Moreover, the drawn fiber still had the ability to undergo elongation under stress, an important fiber property.

Another important discovery of the research team was the fact that the drawn fiber polyester appeared to be nearly as strong when wet as it was when dry. This was very definitely an improvement over natural man-made cellulosic fibers or yarn. When investigated by x-ray diffraction the polyester fiber showed orientation of crystalline phases similar to that of silk and rayon fiber. It was later observed that polyester could be dry spun from chloroform like acetate rayon, and it could also be cold-drawn.

The research group of synthetic chemists was able to prepare linear polyesters having molecular weights above 10,000 ("superpolymers") which were fiber forming. However, because of their low melting points, their lack of stabilities, and their solubilities in a number of solvents, the polyesters did not show promise as textile fibers at that time. The useful properties of polyesters for fibers were not recognized until additional important concepts and properties associated with aromatic polyesters were discovered by J.R.Whinfield and J.T.Dickson at the end of the 1930's.

Without the benefit of future knowledge about aromatic polyesters, the Carothers group concentrated its research on the polyamides synthesized in the early 30's. The synthetic polymer which was chosen for fiber development was that synthesized from hexamethylenediamine and adipic acid in the mid 30's. Each one of these monomers contains a small six-carbon chain and so the polyamide synthesized from these monomers was referred to as a 66 polymer, later called "Nylon 66." This was the synthetic polymer that engineers with fifteen or so years experience in the rayon textile field devoted their attention to as development of nylon was commenced. The basic principles of the synthesis and the needs for high molecular weights and fiber orientation were established.

The Engineering

Looking back, one of the first attempts to market an unnatural fiber came in the last half of the 19th century when collodion was extruded into fine thread and woven into fabric as an artificial silk. The high flammability of this material contributed most to its failure, but weakness was also a very significant shortcoming. The widespread use of silk in clothes, household furnishings, parachutes, fish line, etc., now attests to the demand for strong fibrous materials. However, much had to be learned in the basic physical sciences before the structural aspects of materials which contribute to strength properties could be explained and exploited for producing synthetic fibers.

Thus, driven by this recognition of inadequacy in MSE in addition to the 20th century need to replace or supplement the supply of silk with a high-strength synthetic fibrous material, observations of the silkworm making its cocoon must have been taken more seriously. The silkworm had long afforded clues for the development of engineering processes for producing synthetic fibers since it was known to extrude a liquid substance through its glands, solidifying into a continuous filament on emerging into cool air. The engineer could simulate this by forcing a substance (either in solution or melted) through a spinneret with small orifices and achieve much the same results, provided that the substance being spun would hang together and subsequently withstand strong stresses or pulling. Only polymeric substances (long-chain molecules) would be capable of this.

Spinning polymeric materials from solution was being investigated before the 1920's in developing the basic art for producing rayon fibers. Chemically degrading high polymeric natural cellulose by either acid (acetate process) or alkali (viscose process) to a somewhat lower molecular weight derivative, and then subsequently regenerating the cellulosic material from solution in the form of fibers had been accomplished. The lowered molecular weight of the regenerated cellulose fibers rendered them weaker than silk fibers which possessed their high natural molecular weight, so that the high strength problem for synthetic fibers had not been solved.

Thus, a large body of knowledge had been amassed and engineering aspects on the spinning and the packaging of rayon for market had been worked out by the time Carothers' group became productive in the preparation of new synthetic polymers. The possible impact of synthetic fibers on the textile industry and society was realized to some extent. The knowledge that linear synthetic polymers of very high molecular weight ("superpolymers") could give rise to high-strength fibers to replace silk for many important applications was already in the minds of astute engineers and scientists. About 1935 the decision to commercialize nylon was made and development problems were handed to the engineers producing rayon (man-made fiber from natural polymercellulose).

Although the research in chemistry did not cease, it was now the time for the engineers (and engineering science) to be drawn upon. Much experience and technical skill had been acquired in the production of rayon and these people had valuable experience in spinning, weaving, and knitting of rayon. Despite the depth of experience in the engineering science of textiles, new innovations and discoveries were required to solve the problems specifically associated with the spinning and weaving of this purely synthetic fiber. Problems in processing and equipment design were immense.

Before a satisfactory solution to the problems of spinning nylon was arrived at, an entirely new concept of melt spinning at temperatures approaching 300°. C was derived. Instead of extruding a solution of polymer into a coagulation bath where fibers are hardened by precipitation (wet spinning) or into a hot gas chamber where fibers are hardened by evaporation of the solvent (dry spinning), the nylon polymer was heated above its melting point of 263° C and the molten polymer extruded into a cool gas chamber for hardening the fiber (melt spinning).

Developing a pumping system for the hot molten polymer requiring small clearances and the use of the polymer itself as a lubricant was an engineering accomplishment in itself. Special non-softening, non-warping, abrasion-resistant steels had to be utilized. Problems involved with properties of polymers could not be handled by classical fluid mechanics based on small-molecule behavior. The engineers were required to confront new design problems to produce new textile equipment since the rayon and acetate equipment was not adaptable to this new synthetic polymer. Nevertheless, they were successful in commencing pilot production of nylon in 1938.

Additional Disciplines

In addition to the contributions of the organic and physical chemists, one might further distinguish a contributing discipline by reference to analytical chemistry. For example, the chemists synthesizing the new polymers were aided greatly by the wet chemical analysis performed by analytical chemists to determine the number of chain ends which were still present in a polymerization mixture. By detecting the number of chain ends in a sample, the analytical chemist could calculate the number of molecules which had linked together to tell him the molecular weight which had been achieved. Analysis and determination of molecular weights of giant molecules was in its infancy around 1930. The development of this analytical capability for polymers gave the organic chemist necessary information from which he could develop reaction conditions to increase and control the molecular weights obtained from the polymerization reactions. As indicated above, high-molecular weight “superpolymers” were required in order to obtain fibers with tensile strengths comparable to that obtained from silk.

During the early days of research on the polyesters and polyamides, another materials science played an important role in the development of synthetic fibers. That materials science was physics. Physicists had previously investigated natural and regenerated natural fibers by x-ray diffraction methods. Diffraction patterns indicating orientation of the long polymer-chain molecules in silk were to a large extent understood and the effects of drawing to orient polymer chains and improve strength in rayon fibers were known. The physicist then developed structure-property relationships of great fundamental importance and contributed greatly to the understanding of the high tensile strength obtained from cold drawing the early filaments produced by the organic chemists. The knowledge of polymer orientation from x-ray diffraction was directly applied to the synthetic fiber research.

Prior developments in the field of metallurgy, as a part of MSE, had to be relied upon by the engineers who dealt with the problems of spinning nylon. When it came time to scale-up the polymerization reactions of nylon, the engineers used copper vessels in initial runs. However, when molten polymer was extruded from the copper vessels it was found to be dark in color indicating the chemical reaction had taken place between the metal vessels and the molten polymer at temperatures approaching 300° C. A search had to be made for different types of materials which were more corrosion resistant in the large-scale environment. Glass vessels were known to be acceptable because these had been used previously in the laboratory. But of all the other materials tested in an extensive search, only silver and stainless steel were found to resist corrosion when in contact with the molten nylon polymerization mixture. Although the technology of stainless steel was still in relatively early stages of development, it was fortunate that significant developments had been made in this area of MSE to be able to furnish a quality of stainless steel which could be utilized under the high temperature conditions imposed by the new melt-spinning method.

APPENDIX 3E

Textured Materials

Textured polycrystalline materials, with physical properties related to those of single crystals, are finding an increasing number of applications in devices where strong mechanical, magnetic, and other physical properties are desired. The feature that distinguishes textured materials from others is the preferential directional alignment of the individual crystalline grains making up the material.

Most materials in use today are polycrystalline aggregates of a large number of microscopic crystals, or grains. The directional alignment among neighboring crystals ranges from random to nearly perfect. We call a material textured when a reasonably good alignment occurs. Thus, a textured material resembles somewhat a giant crystal. Because a crystal may be mechanically stronger or more magnetic in one direction than another, properties of polycrystalline materials can be enhanced by texturing.

Recently-developed textured materials are being used for permanent magnet alloys in electronic and electrical equipment, for magnetic memory devices called twistors, and for high-strength phosphor bronze and other copper alloys as springs in relays, connectors, and many other devices.

Texture is developed in several ways. One method starts with cast ingots. When an ingot is deformed, such as by rolling or wire drawing, textural changes take place. Interestingly enough, the crystals often do not assume random orientations when the deformed material is subsequently annealed. A new set of crystals forms by recrystallization, and the new crystals often take on a new texture with a different orientation from the old texture.

Recent researches have led to advances in understanding how texture is developed—an essential first step in the control and exploitation of this phenomenon in materials.

In one study, undertaken by two research metallurgists, the formation of texture in castings was simulated and followed by observing the steps by which freezing occurs in certain transparent, nonmetallic materials that possess thermodynamic properties similar to those of metals. The study of castings of these transparent materials has led to better understanding and control of texture in castings. An impressive application of texture control by casting is in the use of directional solidification for turbine blades for jet engines. Other metallurgists concerned with finding improved magnetic alloys have, quite recently, also employed directional solidification to enhance the magnetic properties of powerful permanent magnet alloys made of cobalt, copper, and samarium (or cerium). Commercial Alnico permanent magnets have likewise been improved by texture control via directional solidification. This type of texture control is most suitable for brittle materials which cannot be mechanically deformed.

If the material is ductile, deformation processes such as wire drawing and rolling can also produce texture. During deformation, certain crystal planes glide over each other, forcing the individual crystals to assume a common directional alignment. These crystal planes can vary from one material to another, thereby producing different textures.

The basic mathematics of analyzing the development of texture during deformation was worked out by the mathematical physicist, Sir Goeffrey I.Taylor, in Cambridge in 1937. The treatment is essentially one of optimization, calling for the selection of a set of slip planes and directions that would accomplish the deformation with a minimum expenditure of mechanical work. Widespread application of the analysis, however, was delayed because of the extremely laborious calculations involved at the time. With the development of linear programming in the 1940's and with the advent of electronic computers, successful application of Taylor's treatment became assured. This was done in collaborative effort between a research metallurgist and a mathematician who have been able to trace the texture development by modeling the deformation on a computer. Graphic computer plots are generated which not only reveal the final texture of the crystals within the polycrystalline material, but how it is arrived at as well. Thus, a considerable degree of textural control can be exercised.

The degree of control over the crystal texture is primarily a function of how the material is deformed. By adjusting die sizes, or the roll spacing through which the metal is passed, the metal is reduced in successive stages. Depending on the sequence and extent of reduction, different textures can be obtained and, therefore, different physical and mechanical properties from the metal. Within the Bell System, such control has led to improved soft magnetic alloys in wire and tape form for use in certain magnetic memory devices, and also to alloys with enhanced mechanical properties for springs and electrical connectors. In the latter, after final heat treatment, yield strengths of such materials as phosphor bronze, nickel silver, cupronickel, and copper beryllium have been, on the average, almost doubled without loss of ductility.

Elsewhere, texture strengthening has been responsible for increased strength in spherical pressure vessels of titanium alloys. In one example, a pressure vessel made of textured Ti-5 Al-2.5 Sn alloy sheet exhibited a yield strength level 40 percent higher than that predicted for randomly oriented material, and the burst strength was about 75 percent higher than that available without texture control. Improved mechanical properties in magnesium and beryllium have also been attained through texture control.

Texture control has been and continues to be a major activity aiming to upgrade the quality of deep-drawing sheet steels. These steels are consumed in huge quantitites as automobile body fenders and appliance housings, to name two of their numerous uses. How deep a cup can be drawn from a blank depends heavily on the strength of the cup wall and on the ease of deformation in the flange region. It has been theoretically predicted, and experimentally proven, that improved drawability can be achieved with the proper texture. In addition, "ears," or undulations of the rim, which must be trimmed away, are directly related to the texture and can be suppressed through texture control. Textured deep-drawing steels are now offered on a limited commercial basis.

These studies emphasize the positive aspects of textured materials. Occasions do arise, however, when texture may be undesirable. For example, some recent work has indicated that thin-film capacitors made from textured aluminum or hafnium film perform poorly as compared to those made from randomly oriented materials. Hence, texture control implies suppression as well as accentuation of texture.

Much work into textured materials remains to be done, but the above examples demonstrate the number and variety of potential applications for these materials. Since certain crystal orientations tend to have better physical properties than others, texture control affords the opportunity to utilize a material's capability more fully.

APPENDIX 3F

Integrated Circuits

The development of the transistor led to a number of basic techniques required for integrated circuits, such as semiconductor purification, crystal growth, alloying, diffusion, oxide masking, and epitaxial growth. The semiconductor industry had reached the point in 1958, when the integrated circuit was born, where it worked daily with crystals of chemical, physical, and structural perfection many orders of magnitude higher than in any other industry, and produced novel, discrete, electronic devices, often with superior performance to that of vacuum tubes.

Silicon was beginning to become important, though germanium was the predominant semiconductor material. Silicon looked particularly promising in military applications where its superior high-temperature performance was necessary. Transistors were being designed into circuits where small size and weight and low power drain were critical, though the cost was still not competitive with vacuum tubes. The first commercial products to use significant quantities of transistors were miniature hearing-aids and portable radios. Computers and communications were obvious candidates in the industrial area, and IBM and BTL had large semiconductor programs. Another was the development of military equipment such as the Polaris and Minuteman missile programs. All of these large-system applications of semiconductor devices spurred the push to miniaturization. This, then, was the status of semiconductors in 1958 when Kilby at Texas Instruments first conceived of and constructed an integrated circuit. Though the practical use of transistors was relatively new, the needs for even further reduction in size, weight, and power were already in sight.

Kilby, an electrical engineer, joined Texas Instruments from Centralab where he had been working on miniaturization of electronic circuits by the silk screening of conductive inks on a ceramic substrate to form resistance and capacitance. Hence, he had experience and a strong interest in miniaturization. In 1958, he conceived of processing the elements of a complete circuit, such as resistors, capacitors, transistors, and diodes in a monolithic bar of semiconductor. The technology for accomplishing this already existed, having been developed for fabricating discrete devices. Diffusion and alloying were used for introducing controlled amounts of desired impurities to create localized p- and n-regions. Metal evaporation and thermocompression bonding were available for making electrical contacts to and between such regions. Kilby's first working semiconductor circuit was a simple phase-shift oscillator with components connected either through the bulk semiconductor when resistance was desired, or by bonding wires between them. This technology permitted fabrication of only simple circuits involving a few tens of devices, and several subsequent advances were necessary before the complex, reliable, and inexpensive integrated circuits of today became a reality. Some of the more important of these advances were made in the continuing effort to improve discrete transistors as mentioned earlier; however, their application to integrated circuits was rapidly recognized and exploited.

The key developments were the application of photoresist and oxide etches to determine the regions into which impurities were to be diffused; the planar process using the above techniques for diffusion but leaving the silicon oxide layer on the surface to protect the ambient sensitive p-n junctions; the use of evaporated and photoresist-patterned metal films on the oxide to interconnect the devices; and the application of chemical vapor deposition for growing thin epitaxial layers of silicon on silicon substrates containing different impurity doping. Each of these developments, and their application to integrated circuit improvement, will be briefly described.

The ability of an SiO_2 layer to mask against the diffusion of many of the group III and V doping impurities was described by Frosch, a chemist at Bell Laboratories in 1957. A wax pattern was applied to the oxide, the unprotected regions chemically etched away to expose the silicon, the wax removed, and impurities diffused into the exposed regions to form p- and n-doped material. Though this technique was useful, it was limited to formation of relatively large regions, several hundred microns in size. Photosensitive materials, known as photoresists, had been developed at Eastman Kodak for the patterned etching of metal on printing plates and on printed circuit boards. These were solutions containing organic compounds which polymerized upon exposure to ultraviolet light. The unexposed resist could be dissolved by appropriate solvents leaving an etch-resistant mask on the metal. Lathrop, a physicist, and Nall, a chemist, working on miniaturization of components at Diamond Ordnance Fuse Laboratory realized, in 1957, that photoresist might be applicable to patterning the SiO_2 for silicons-diffused transistors. This allowed windows of the order of 200 μm in size to be etched. Continued improvements in photoresists, with emphasis on their use with semiconductors, increased their definition capabilities to about 25 μm by 1960 and to less than 1 μm today. A major advantage in these photoresist techniques is the ability to pattern all of the areas on a two-inch diameter silicon slice simultaneously, with consequent reduction in processing cost.

The next major technological advance was the planar process, developed by Hoerni, a physicist at Fairchild. This process applies the oxide-masking and photoresist technologies already described; however, SiO_2 is regrown into the windows during the diffusion steps and the oxide is left over all of the device or circuit surface except the contact areas. This has two major advantages, The oxide, as had been shown by Atalla, eliminates slow surface states and protects the sensitive regions (where p-n junctions intercept the silicon surface) from the effect of ambients, thereby leading to improved device characteristics and greater reliability. Also the oxide is a good insulator and allows evaporated metallization patterns connecting the devices to be formed directly on the oxide surface. Again, photoresist techniques are used to define these metal interconnection patterns. It is also possible, by depositing another SiO_2 layer over the first metallization, to then form a second set of interconnections allowing even more complex circuits to be fabricated.

Still another significant development necessary for the success of integrated circuits was the application of chemical vapor deposition to grow epitaxial silicon layers. Circuits made with planar technology, but on bulk silicon slices, had severe limitations. Many circuits required significantly better electrical isolation between individual regions or devices than was afforded by the bulk silicon resistance alone. Hence, such circuits could not be integrated. Epitaxial growth, as will be described, allowed suitable isolation to be achieved.

Chemical vapor deposition for growing single crystals of silicon and germanium was demonstrated in the early 1950's by Sangster, a chemist at Hughes, and by Teal and Christensen, chemists at Bell Laboratories, The conductivity type and resistivity of the deposited semiconductors could be controlled by introducing appropriate impurity gases during the deposition. Several investigators attempted to use this technique for growing successive multiple n- and p-type layers to form diodes and transistors directly, rather than by starting with uniform material and altering regions by impurity diffusion, However, these attempts gave poor results. The characteristics of the resulting p-n junctions were poor, probably due to imperfections or contamination at the interfaces between the layers. And whereas diffusion could be patterned into localized areas, there was no comparable way of patterning the epitaxial regions. However, a interdisciplinary team at Bell Laboratories, Loar (physicist), Christensen (chemist), Kleimack (physicist), and Theurer (metallurgist), realized and demonstrated that a more limited use of epitaxial deposition could significantly improve planar transistor performance.

The diffused base and emitter regions in planar transistors are quite shallow, extending only a few, or at most a few tens, of microns in from the silicon surface. Yet, in order to be handled during processing without excessive breakage, the silicon slices must be several times that thick. Since the resistivity in the collector region adjacent to the base needs to be of the order of 1 ohm-cm, the extra thickness adds additional collector series resistance which is detrimental to transistor performance. By starting with a heavily doped, hence low resistivity, silicon slice of sufficient thickness to provide the necessary mechanical strength, and growing a lightly doped epitaxial layer only thick enough to contain the active regions of the transistor, a significant reduction was obtained in collector series resistance.

This same technique was subsequently applied to silicon integrated circuits to achieve electrical isolation between components. A thin n-type epitaxial layer suitable for fabrication of the desired devices was grown on a p-type silicon substrate. During processing, a group III impurity was diffused through the thin n-layer to the p-type substrate in a pattern that surrounded those devices requiring isolation with p-type material. The high resistance of the reversed bias p-n junction provided the isolation.

Based on the technologies which have been described, integrated circuits containing bipolar transistors as the active devices were developed to perform a variety of electronic functions, and a major commercial business resulted. Meanwhile, back in the laboratories, a new active semiconductor device was being studied, the metal oxide semiconductor transistor. It is interesting to note that the MOS transistor is in essence, the field-effect device that Shockley had originally sought, but only more recently made possible through advances in materials technology. This device had significant advantages over bipolar transistors for some applications. The electrical power requirements were lower. High packing densities on integrated circuits were possible. And fewer processing operations were required during manufacturing, resulting in higher yields and lower costs. However, the device also brought new technical problems which had to be solved before its usefulness could be realized.

Inasmuch as the critical, active region of the MOS transistor lies very close to the silicon-SiO_2 interface, the instabilities in the SiO_2 and near the interface strongly influence the transistor properties. Such instabilities can be caused by many things, a common one being the presence of sodiumion contamination in the SiO_2. The high electronic field present across the oxide during operation of the device causes the sodium to migrate, and transistor characteristics shift accordingly. Many man-years of effort in several laboratories by chemists, physicists, and electrical engineers were required before the causes of, and cures for, these instabilities reached a point where reliable MOS integrated circuits became practical. This area is now growing rapidly in importance, with integrated circuits containing as many as 10,000 individual components being manufactured in high volume and incorporated into equipment such as electronic desk and hand calculators.

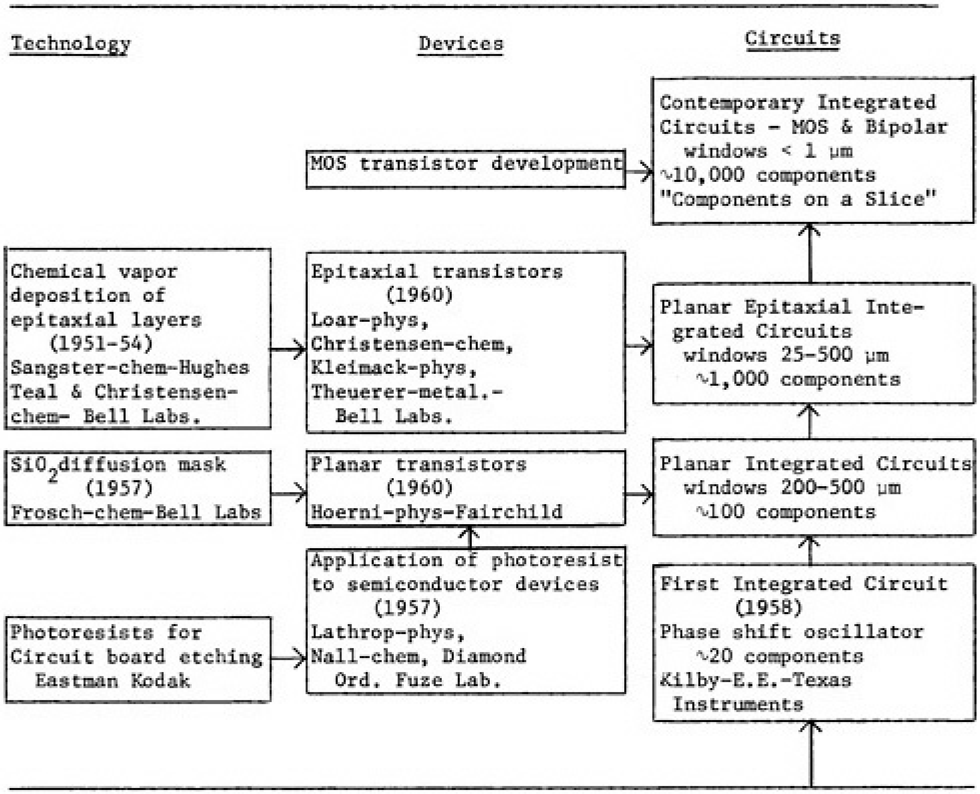
So the integrated circuit has evolved, in a little over a decade, from Kilby's first phaseshift oscillator with a few components to the large-scale manufacturing of circuits with over 10,000 components; and these at much lower cost and higher reliability than the sum of the individual components.

The critical steps in the integrated-circuit story are shown in Figure 3.3.

The Role of Materials Science and Engineering In Integrated Circuits

The overall effort was both multidisciplinary and interdisciplinary. Chemists and metallurgists developed epitaxial growth techniques with the scope of the studies ranging from basic investigations of the kinetics and thermodynamics of the vapor-solid reactions to the design of production reactors capable of handling several slices at a time. A chemist discovered the diffusions-masking ability of SiO_2. A physicist, who had previously spent several years in a university chemistry department, conceived of the planar process. A physicist and chemist first applied photoresist methods to semiconductors. Metallurgists perfected the metal systems evaporated onto the surface for interconnecting the components. Electrical engineers designed the devices and circuits, and laid out the diffusion-masking and interconnection patterns such that circuits would perform the desired functions. Today, because of the extreme complexity of circuits containing in excess of 10,000 components, layout and interconnection patterns are performed on computers, requiring programmers and software specialists, and they must interact

Figure 3.3 Key Integrated-Circuit Developments, 1958–1971



SOME PRE-INTEGRATED CIRCUIT DEVELOPMENTS INVENTION OF:
Point-Contact Transistor–1948
Junction Transistor–1949
WORK BY:

Chemists & Metallurgists on growing, purifying and doping crystals. Grown junction, alloying and diffusion processes.

Physicists on recombination mechanisms, carrier transport, band structure, surface states.

Electrical Engineers on transistor design, power and frequency improvement, circuit design.

closely with the chemists, physicists, and process engineers to assure compatibility between the design and the process capabilities. Finally, metallurgists and ceramic engineers developed the hermetically sealed packages to protect the silicon circuits.

Interaction between science and engineering certainly existed to a high degree. While investigators were busy writing up their work for publication in scientific journals, they were simultaneously phasing their developments into the production lines. The time between scientific advance and production was extremely short.

The technological advances described here borrowed very heavily from developments in other areas. Nearly all were motivated by attempts to improve the performance of discrete transistors rather than integrated circuits. Diffusion of impurities had been studied for years in other materials, such as metals. Photoresist was developed for the printing and circuit-board industries. But those concerned with the perfection of the integrated circuit quickly recognized the applicability of such techniques.

There were certainly many individuals and institutions involved, both in the initial discoveries and even more in the subsequent development into useful processes. Few of the significant contributions to process technology involved basic research. Most grew out of applied research and engineering, with the latter predominating.

The development of integrated circuits, in fact the entire development of modern electronic devices, was not only a case where the MSE approach was followed, but one where this approach was essential for success to be achieved so effectively.

APPENDIX 3G

Aluminum Conductor Telephone Cables

Introduction

In 1965 the Bell System undertook an extensive development project with the specific aim of establishing an aluminum-conductor telephones-cable technology as a commercially viable alternative to copper conductor cable. This goal was accomplished, and the problems overcome in reaching it are outlined in the following section. The major impetus for this development, as with most other substitutions of aluminum for copper in electrical applications, stemmed from periodic instabilities in both the price and availability of copper and the growing cost differential between these two metals. As the largest single consumer of copper in the U.S. (approximately 270,000 tons or 14 percent of all the copper processed in the U.S. in 1971), the Bell System is particularly vulnerable to these factors.

Problems in Substituting Aluminum for Copper In Telephone Cables

The problems divided themselves into design and manufacturing categories. The former focussed on providing a cable and connector technology of equivalent electrical, mechanical, and reliability performance to that achieved with copper. The latter focussed on developing a manufacturing process as fully compatible as possible with the high-speed tandem operations of wire drawing, annealing, and insulating, now used for copper. The hallmarks then were equivalent reliability and maximum compatibility.

The problems posed by aluminum itself include:

(a) Its lower electrical conductivity (= 65 percent copper standard).
(b) Its highly resistive and quick-forming oxide.
(c) Its high electropositive potential.
(d) Its normally poor combination of strength, ductility, and creep resistance when high (>60 percent) electrical conductivity is sought.

These problems are not serious for electric-power transmission lines nor for motor and transformer windings when properly designed. Communication cables and building wire do present serious problems arising particularly from (b), (c), and (d).

These difficulties were dealt with in the aluminum-conductor telephone cable as follows:

(a) To meet current cable transmission requirements and provide equivalent copper conductivity, the electrical conductivity of aluminum was specified as 60 percent copper standard and a 2-gage size larger cross-section was used. (The cable size penalty incurred in adopting aluminum alloys with less than 60 percent arises not only from larger conductor cross-sections but also from thicker insulation needed to maintain cable capacitance requirements.)
(b) Oxide characteristics required a pressure-type connector capable of providing a gas-tight joint under thermal cycling and conductor creep. This was accomplished with an indium-plated, phosphor bronze, knife-type connector shown to maintain satisfactory contact resistance,
(c) The electrolytic and galvanic corrosion properties of aluminum necessitate exclusion of moisture from the conductor and from connectors where dissimilar metals are in contact. The extruded polyethylene wire insulation is the primary conductor moisture barrier; the new cable sheath with a continuous aluminum foil barrier is the second; pressurized gas or petroleum jelly filling in the cable is

the third.* The connector housing was also filled with an organic gel.

(d) Although the desired strength and ductility of electrical-grade aluminum was satisfactory for wire sizes of 17 and 20 gage, a new alloy was required for 24-gage wire. An Al-0.8Fe-0.12Mg was developed for this and subsequently found to have creep properties comparable to toughs-pitch copper and far superior to electrical-grade aluminum.

In the area of processing, the aluminum-alloy producers were convinced of the need to use liquid-metal filtering to achieve low wire breakage on drawing. A new cleaning and inductions-annealing procedure was adopted and an H-11 temper (20 percent reduction in area) was found to give the best combination of strength and ductility.

Observations

The aluminum industry was initially reluctant to participate strongly in this program, questioning both the size of the market and the need for further alloy and processing development in this area. When convinced, however, they participated actively, and provided the new Al-Fe-Mg alloy which they are now promoting for this and other electrical applications. The Bell System worked with the major U.S. aluminum producers in this development and the functional interactions were with the working-level plant metallurgists in these organizations. On the producers' side, marketing and sales people provided a strong stimulus when made aware of the market potential and research people became involved at the later stages to "fine tune" pragmatic solutions already reached.

There is no unique example of technology-transfer either into or out of this case but several associated technologies, e.g., connectors, were affected by the substitution, and parallel programs were needed to solve these problems. This lengthened the program's duration (approximately 5 years) and emphasized critical-path considerations and the desirability of a systems approach. Having solved the basic problems in an all-aluminum conductor system, the expedient nature of a copper-clad aluminum substitution becomes more apparent.

APPENDIX 3H

Polymer Latex-Modified Portland Cement

A "polymer latex-modified portland cement" is obtained when a part of

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* Historical note: In the early 1950's, the Bell System experimented with an aluminum conductor telephone cable employing paper-pulp-insulated wire. These cables failed catastrophically in the field due to electrolytic corrosion in the presence of the applied voltage and ingressed moisture from cable-sheath damage. This failure posed a psychological barrier to acceptance of the new cable which was only slowly overcome with successful field performance.

the water quantity that would be required in mixing a conventional (i.e., non-polymer containing) composition is replaced by colloidal polymer-latex particles. This modification, with appropriate latexes, is sometimes accompanied by significant alteration of properties in the resultant material as, for example, enhancement of compressive, tensile, and shear strength values, altered elastic moduli, improved resistance to chemical attack, and increased adhesion to various substrates.

In many instances, the increases in tensile strength and bonding characertistics have been so dramatic (as with brick mortars) that new structural cesigns and fabrication methods become feasible. In other situations, upgraded chemical resistance, or bonding properties, has allowed introduction of portland-cement-base compositions into applications earlier considered impractical. Methods of installation or of repair (as with surfacing compositions or precase concrete wall-panel patching) have been enabled or simplified.

Many individuals and many organizations have contributed to the development of polymer latex-modified portland cement. One group’s efforts are described here to provide an explicit example; the description is intended as representation of the contributions made by MSE in this field.

The People

The three principal investigators have been:

Herman B.Wagner, Professor of Chemistry at the Drexell University, a physical chemist experienced in organic polymers and hydraulic cements.

Dallas G.Grenley, a polymer chemist at the Dow Chemical Company, experienced in polymer latex synthesis.

Jerry Isenburg, a physicist at the Dow Chemical Company, specializing in portland cement rheology and scanning electron microscopy.

Each of the above individuals has been intimately acquainted with polymer modified-portland cement compositions for a number of years, from the chemical, engineering, and commercial aspects.

The Program

When this program was started in 1961, there was a considerable amount of empirical data relating to such gross variables as identity of the polymer modifier, the level of polymer content, and environmental conditions surrounding the cement hydration (hardening) reactions. No mechanism had been established for the observed reinforcements of cement by certain polymers although numerous suggestions had been put forward. This interdisciplinary team set out to establish a more basic understanding of such systems in terms of the physical and chemical interactions between the polymer and cement. Earlier research in physics and chemistry, entirely unrelated to cement technology, provided the necessary experimental tools.

Some Preliminary Considerations

The results obtained up to this time are best presented with reference first to an unmodified cement composition. With a typical portland cement powder, tricalcium silicate and betadicalcium silicate constitute about three-quarters of its weight. Under ordinary temperature conditions, and with only water available, the hydration of these two major constituents is essentially complete within 7 days. Hydration of other constituents requires considerably longer for completion. In any case, the "cement gel" that is progressively developed as the product of these hydration reactions comprises chemical species of high specific surface. The new surface area that can ultimately develop may be 500 to 1000 times larger than that of the initial cement grains, and the strength properties of the hardened cement are importantly linked to this increased surface area, and to the structure and packing density of the colloidal hydration products.

A polymer latex may be visualized as relatively uniform-diameter (e.g., 2000 Å) spherical polymer particles colloidally dispersed in water. Here, typically, one-fourth of the volume of the latex would be an organic polymer, such as polystyrene, and three-fourths of the volume water. Additionally, small concentrations of surfactants, soaps, polymerization initiators, and other minor constituents required for manufacture or stabilization of the dispersion are also present. When such a latex is mixed with the cement powder, a fluid suspension of the cement grains is initially obtained. This fluidity is imparted not only by the water but also by the polymer particles which are considerably smaller than the cement grains.

Following this mixing, one might expect or visualize a number of events and effects, including (a) progressive hydration of the cement grains, as with conventional cement, (b) coalescence of the latex particles with one another, as the dispersant water phase is consumed by the cement-hydration reaction, (c) modification of the rate and/or course of the hydration reactions caused by the presence of the polymer latex particles or other constituents of the latex, (d) physical attachment or chemisorption of the latex particles at the surface of the cement grains and/or cement gel, (e) chemical reaction of the polymer latex in this environment, altering the character of the polymer surface presented, etc.

Experimental Methods

Among the experimental techniques employed in this investigation were transmission and scanning electron microscopy, electron probe, infrared spectroscopy, electrophoresis, BET absorption, and radio-isotope tracing. Special techniques and apparatus have been developed by the various investigators to obtain data on coalescence, adhesion, surface adsorption, mortar rheology, and engineering properties. As one example, the tremendous depth-of-field of the scanning electron microscope has been exploited in studying the cement structure in convenient steps of magnification from 20 to 100,000X. The morphology of the cement grains is thus found to be altered by the hydration reactions, and the various crystalline forms can be observed. The very small latex particles are perfect spheres in the mortar mixes, but upon drying they coalesce to form a continuous film in which the individual particles lose their identity.

Conclusions

The development of polymer coalescence was found to occur gradually, over a period of hours to days, and the structure of the coalesced polymer within these compositions was detailed microscopically and related to the inorganic components. The rate of generation of specific surface area of the cement gel was retarded by some latexes and accelerated by others; ultimately the surface area developed is not affected by the latex type, and the chemical structure of the cement gel is comparable.

The enhanced compressive strength observed is primarily the result of densification of the cement gel structure. Tensile and adhesive strength increases, on the other hand, are determined by levels of bonding that are affected between cement and aggregate interfaces and within the hardened cement paste; these are specific to the chemical latex employed.

Moduli of elasticity and rupture were found to be related to extent of cement hydration achieved and to specific effects of the polymer or interfacial adhesion.

A detailed picture of the structural and chemical events occurring as such compositions harden is being assembled, and it is expected that a systematic procedure for developing effective latexes and polymer-modified materials is emerging.

APPENDIX 3I

Phosphors for TV

The story of phosphors is a rich one, extending back many decades in fundamental studies of the interaction of light and matter. Throughout the same period, phosphors have played an important technical role, for example, in creating luminescence on cathode-ray screens. In even such as limited a field as red phosphors for color TV screens, there has been a wealth of contributions from several major laboratories. A team of workers at the Philips Laboratory independently discovered the potential for color TV applications of europium-doped yttrium oxide phosphors and the related material, gadolinium oxide. Others had independently explored oxy-sulfide systems and had developed the yttrium compound Y_2O_2S: Eu. The following is a description of the development work of three individuals at the General Telephone and Electronic Laboratory in Palo Alto, which led to the development of the new red phosphor of commercial importance. While singling out one group has the effect of neglecting the important contributions of others, the intent here is to portray as specifically as possible one material development characteristic of MSE and to identify precisely the various elements of the situation. For present purposes, the details of one specific development, which were readily available to us, seem to outweigh the advantage of the usual scientific custom of giving due credit and reference to all significant contributions

Early color TV screens were limited in brightness by the characteristics of the red phosphor. The blue and green phosphors were operated at reduced electron current to balance with the red phosphor which exhibited current saturation and a color short of bright red. In 1961, an interdisciplinary team at General Telephone and Electronics developed a new red phosphor material with a redder color and a capability of operation at higher energies. All TV tubes manufactured in the U.S. now use this phosphor, or rare-earth compounds subsequently developed by other organizations. The host material is yttrium oxide, which is durable and has good optical properties. The activator which fluoresces and emits the desired (red) light is europium, a rare earth. This material has a high efficiency for cathode-ray excitation. A similar oxide, yttrium vanadate (YVO_4), which was recognized as a good phosphor through the yttrium oxide work, has been shown to give an even redder emission color (desirable for TV) although somewhat less efficiently.

The People

As is true in every MSE effort, the people are of central importance. The three principal investigators were:

Robert White, trained in physics, with experience and emphasis on magnetic materials and resonance phenomena.

Kenneth Wickersheim, trained in physics and specialized in optical spectroscopy.

Robert Lefever, trained as an inorganic chemist with considerable experience in materials preparation and crystal growth.

These three individuals, with different backgrounds and different areas of specialization, maintained a high level of interaction on a daily basis. Each of them had an interest in and a detailed knowledge of the other's current programs. Each understood how his work could influence and could be influenced by that of the other two.

The Program

It is important to note that the program pursued by these three researchers had as its original objective not the development of new phosphors, but rather the development of suitable host materials for lasers. The rare earths were identified as promising candidates for laser materials because of the sharp line spectra which are characteristic of rare-earth ions. The sharp lines result from emissions in the 4f shell which is shielded from the local environment by the completed 5p shell. It is this same shielding which leads to the close chemical similarity between the rare earths and yet provides a selection of strong optical lines by choosing different rare earths. There had been some previous experience with rare-earth activators for phosphorescence but much of that had been discouraging. With the insight gained by the work now being described, it is clear that rare-earth impurities had caused line quenching in some cases and that the host material had not been suitably chosen. It now appeared that the rare-earth oxides in cubic form would be desirable hosts in that the material is refractory, has the proper crystal symmetry, and is chemically stable. These physical and chemical properties plus extensive knowledge of material-growth techniques, optical absorption and emission, as well as interaction of dopant atoms with the host lattice, made the rare-earth oxide approach seem promising.

Knowledge Required

Fortunately all the fundamental science necessary for this development had been completed, and these investigators were familiar with the considerable span of knowledge required for proper pursuit of this materials development program. In addition, close interplay was achieved between a knowledge of growth of refractory oxides and a knowledge of line-broadening mechanisms which are the principal road block in the achievement of good phosphors.

Lefever had previous experience with the use of flame fusion (Verneuil) techniques for the production of single crystals of refractory oxides through growth of refractory oxides for his studies on ferromagnets. The standard Verneuil apparatus is a concentric-tube oxy-hydrogen burner in which the center tube is used to supply the raw material for crystal growth and oxygen. From this work and related studies on flux growth of crystals, he gained a detailed understanding of the importance of crystal imperfections and impurities on radiation line widths (in this case, radiating in the RF frequency range). A particular example, discussed later, is the presence of silicon in yttrium-iron garnet which leads to line broadening by an intermediate process. This experience emphasized that specific impurities can be important in an almost unique way when one is considering a particular physical process. It is impossible to eliminate all foreign impurities from a single crystal, but it may be possible to reduce to an extremely low level one or two foreign species which are particularly troublesome.

Phosphorescence is a material phenomenon in which energy introduced into the material by electron bombardment or ultraviolet radiation is partially re-emitted over a period of time in the visible spectrum. Normally the light is emitted from impurity atoms which serve as activators. Mechanisms which reduce the efficiency of phosphorescence include poor transfer of the absorbed energy to the activator, nonradiating energy loss from the excited activator, and line broadening of the spectrum of the activator atoms.

Line-broadening mechanisms are attributed to many physical processes, all of which need to be understood in a detailed analysis of the behavior of a particular phosphorescent material. In a solid, the optical emission lines are usually very broad and often indistinguishable because there are so many ways in which the energy levels can be varied by influences from neighboring atoms. This variation is found for well-defined positions in single crystals. The electron bond to an individual atom can have its energy level changed by a large variety of physical mechanisms, some of which are discussed briefly. The sum of these interactions leads to a statistical distribution of energy for the large number of atoms involved in any real sample, and the result is a broadening of the emission line.

Crystalline field splitting is the term used to describe variation in energy level due to the interaction between the electric fields in the crystal and a specific electron state or orbit. If the electron state is not spherically symmetrical and if the crystalline field varies along major directions of the lattice, the energy level will depend on the relative orientation between the electron orbit and the crystal.

A low-symmetry atomic site can be beneficial when the desired line is forbidden as is the case in the europium 4f shell. Y_2O_3 has two rare-earth acceptor sites, one of moderately high symmetry and one of very low symmetry. This was an important reason for choosing Y_2O_3.

Lattice vibrations are a frequent source of line broadening. The lattice is not rigid but rather is in a continual state of vibration due to thermally-induced stationary mechanical waves. Solid-state physics has developed an elegant way of treating these vibrations in terms of phonons which can be much more readily manipulated theoretically. Phonons are a mechanical analogy to electromagnetic quanta. They represent a discrete energy of activation and may be thought of as particles in their interaction with other entities such as the electron bound to an atom or an electron in the conduction band of a solid. Phonons are created or destroyed depending on whether energy is added to or taken from the mechanical system. If a phonon interacts with an electron at the time of emission, the line may be of longer of shorter wavelength depending on whether a phonon is created or destroyed. Y_2O_3 was known from infrared spectroscopy to have a phonon spectrum which coupled weakly with photons in the visible region and therefore contributed little line broadening.

Exchange forces which lead to exchange splitting are a purely quantum-mechanical effect which has no classical analog. Fundamental particles, such as the electron, are identical to the extent that there is no observation which can be made to distinguish whether the particles have exchanged places. If two electron orbits share some common space (wave functions overlap), it is possible for them to exchange positions. The effect on the energy level of each orbit will depend on the relative alignment of the electron spins. This phenomenon is called exchange coupling and is most important in solids when magnetic ions are involved.

Magnetic fields can also change the energy of the electron state. Every electron has an intrinsic spin with which is associated a magnetic moment. The magnetic moment can interact with a magnetic field. In addition, some states of the electron can be thought of as having an associated electric current which interacts with the magnetic field. Magnetic interactions are of course particularly large in materials containing the transition metals such as iron and nickel with their large magnetic moments.

Resonance broadening is an important concept to understand in studying line radiation from solids. If an electron state is weakly coupled to another of identical frequency, resonance will occur between the two and the electron energy will be perturbed, leading to a broadened line. The GT&E group had done a considerable amount of work on ferrites and garnets where resonance is an important phenomena in line broadening in the radio-frequency spectrum. The work on garnets illustrates the close coupling between material preparation and its use; it set the stage for the phosphor development. Wickersheim and Lefever had earlier identified the presence of a silicon impurity in the yttrium-iron garnet at the tetrahedral oxygen site. The silicate ion is incorporated in a tetravalent state in contrast to the trivalent cations in the normal host material. The quadrivalent silicon provides a mechanism for incorporation of a compensating divalent ion to maintain charge neutrality. It has been hypothesized that ferrous iron is introduced from the melt to provide the divalent ion. White had recently provided some confirmation of a theory by Kittel, Portis, and de Genes on line broadening of the magnetic resonance which occurs at a few gigahertz. Fe^{++} is strongly coupled to the magnetic lattice and in turn is coupled to the rare earth ion by resonance. The result is an easy path for draining energy from the activated atom to the lattice. From this experience, these three investigators were well sensitized to the degree to which the nature of the host and impurities might need to be controlled to obtain narrow-line radiation from a rare-earth activator and consequently high efficiency.

Research Environment

The research environment was an important element in this example of MSE. This work was carried out in an industrial laboratory where there was considerable latitude available to the investigators to pursue directions which they believed to be most promising. At the same time, the program was being carried on for an applied purpose. Because of the close relationship between GT&E Laboratory and Sylvania, an operating Company, it was well known in the Laboratory that the TV industry had need for improved colored phosphors for the cathode ray tubes and the nature of the required improvements. As a result, a span of knowledge was achieved which extended from scientific investigation to commercial application.

There was an extremely close working interaction between the three individuals of different background and training. In particular, there was a thorough understanding of just what material characteristics were desired and how they should be reflected in the physical properties of the material. This knowledge was not something which was established a priori and left fixed through the life of the project. Rather, the close interaction modified and refined the material characteristics and requirements as the project developed. With respect to the phosphor development, most of the close interaction required had already been accomplished in the garnet work.

Yttrium oxide was chosen as a laser-host candidate for several reasons. First, the symmetry of the crystal sites for europium were known to be of low symmetry, that is, the local crystal fields vary with direction. Low symmetry is desirable because it removes the forbiddenness of some important 4f transitions in the rare earths. Second, Y_2O_3 has a phohon spectrum which couples weakly with the excited levels of the excited europium activator. The weak coupling increases the probability that excitation energy will be emitted optically rather than by transfer to the crystal without optical radiation. Third, Y_2O_3 had already been grown by Lefever; its optical transmission had been measured by Lefever and Wickersheim and was known to be appropriate. Fourth, Y_2O_3 accepts trivalent europium at a trivalent site. In previous laser material, the rare earth had replaced a divalent ion giving rise to charge compensation and therefore a crystal defect for every activator resulting in line broadening. Y_2O_3: Eu was the only material chosen for initial studies. The extensive and detailed knowledge in hand precluded the need for a systematic empirical search through many materials.

Results

Lefever was able to grow yttrium-oxide single crystals with europium doping. In order to do so, he had to develop a modification of the flame fusion burner, and then in order to prevent cracking of the crystals he devised a technique for protecting the growing crystal with a coating of powder which reduced thermal gradients in the crystal. Both improvements were patentable.

When the first sample of europium-activated yttrium-oxide laser crystal was examined in the spectrograph under ultraviolet excitation, it was immediately evident to the eye that this was a superior red phosphor. Few scientists in any field are privileged to make a discovery in such a dramatic and instantaneous way. Because of the commercial interest in cathode luminescence, apparatus was built to measure the light emitted due to electron bombardment. The europium-doped yttrium oxide was found to emit a red line of brightness comparable to the green phosphor (willemite) under identical excitation conditions. The color was redder than the red TV phosphor in use at that time, accepted high beam currents without saturating, and emitted efficiently even at elevated temperatures.

It is important to remember that the objective of the program was development of a hardy, sharp-line laser material, a goal that was achieved. However, as a result of understanding the properties of the material and an awareness of technical requirements for improved phosphors, the potential value of Y_2O_3: Eu was immediately recognized and, because of program flexibility, efforts were channeled into further work on the phosphor aspect of the material.

Much work has been done subsequently by others on rare-earth phosphors for TV applications. Such work was stimulated in large part by the Palo Alto GT&E group and later studies at Sylvania and the GT&E Bayside Laboratories.

APPENDIX 3J

Sintering of Ceramic Oxides, e.g. Lucalox

Better understanding of the driving forces, material-transport mechanisms, and kinetics involved in the sintering of ceramic oxides, has been evolving over the past 30 years. The understanding is not yet complete, but knowledge already grained has led to better control of manufacturing processes and improved properties in many ceramic products.

Early theoretical work that contributed to this progress was that of the Russian theoretical physicist, J.Frenkel, who published a paper in 1945 on “Viscous Flow of Crystalline Bodies Under the Action of Surface Tension.” In 1950, a theoretical physicist at Bell Laboratories, C.Herring, published two papers entitled “Effect of Changes of Scale on Sintering Phenomena” and “Diffusional Viscosity of a Polycrystalline Solid.” At approximately the same time, a third theoretical physicist, F.Nabarro at Bristol University in England, made similar studies and today there are frequent references in the ceramic literature to the “Nabarro-Herring diffusion creep model.”

Another major contributor at about this time and continuing to this day was the metallurgist, G.C.Kuczynsky at the University of Notre Dame, who developed quantitative models for sintering rates and checked them experimentally with metal and glass macroscopic spheres as well as with fine powders. He was the first to demonstrate experimentally in metallic systems that mass flow can occur by volume diffusion during sintering. The ceramists, W.D.Kingery and M.Berg in 1955, were the first to do so in oxide systems. However, the person who is responsible for the first commercial product to be developed based on fundamental studies of sintering is the ceramist, R.L. Coble. This occurred around 1958 and the product became General Electric’s Lucalox. This is a transparent polycrystalline aluminum oxide of nearly theoretical density containing 0.1 to 0.25 percent of magnesium oxide concentrated at the grain boundaries which acts as a grain-growth inhibitor. Competitive products are now also available from Coors (“Vistal”), Philips, Sudplastik, and Keramik, etc. The principal application is as envelopes for high intensity, sodium vapor lamps.

Related development of useful products has been extended to ceramics whose major components are yttrium oxide (G.E.’s Yttralox for infrared-transmitting windows), magnesium aluminate (possibly a superior material for high-intensity lamp envelopes), and magnesium oxide (for potential applications as transparent armor). It should be noted that all of these compositions are relatively simple. The first extension to more complex materials is the development of the lanthanaum-doped lead zirconate titanate systems (first at Sandia) for purely optical applications such as optical switching, optical memories, and image-display devices.

APPENDIX 3K

Interdisciplinary Research—An Exploration of Public Policy Issues*

Roadblocks to Interdisciplinary Research

Professionals trained in a given discipline speak a special language, use their own methodologies and scientific tools, and may consider one part of

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* Library of Congress, Science Policy Research Division, Prepared for Committee on Science and Astronautics, U.S. House of Representatives, 30 October 1970.

a research problem significantly different in importance from another disciplinary professional.

Disciplinary orthodoxy and differences between disciplines are items which have varying import for the concept and conduct of interdisciplinary research in various institutional settings. Possible issues are outlined and described below:

1. Disciplinary Orthodoxy May Produce Strains in Doing Interdisciplinary Research:

The most important and obvious difference is the fact that interdisciplinary research brings together persons with different foci of interest as well as different conceptual systems. These systems have potentialities for integration, but they also have strong tendencies toward competition. A second factor is the differential status of the disciplines. This has a bearing on both the formal and the informal structure of the research team and its administration and plays an important part in determining the handling of the decision-making process. Closely related to this are the expectations, stereotypes, and images, overt and covert, that members of one discipline hold regarding persons trained in other fields. These may have an important bearing on interpersonal relationships. Fourth are the differences in methodology among the disciplines, together with subtle and often unrecognized differences in philosophic orientation and ideology, which tend to have some relationship to disciplinary affiliation and to bring members of some disciplines more closely together than those of others.

2. Disciplinary Differences May Produce a Power Hierarchy, Inhibiting the Conduct of Effective Interdisciplinary Research:

When interdisciplinary research takes place within complex research organizations, participants are unlikely to have equal formal or informal status, which would produce strains in the relationships…The differences in background, status, skills, and values that participants bring to the group could lead to a struggle for power. This is a serious problem…

There are many difficulties in getting these groups to operate smoothly. When there are struggles for power, research activities probably suffer. Relations of power become involved in making decisions about the selection of problems and techniques and the necessary tests for the validity of results. Each kind of specialist approaches the problem area from his own perspective and is often incapable of understanding the approaches of others; he may interpret the arguments of others as devices to win power, and they may be precisely that. Perhaps a “least common denominator” approach comes to be used in the selection of problems and concepts. When this happens, significant theoretical findings are unlikely to be obtained.

3. Uneven Levels of Development of the Disciplines Involving Interdisciplinary Research Make Collaboration Difficult:

The readiness of the particular disciplines to cooperate in a specific problem is an important criterion. To be ready for interdisci plinary research, the disciplines involved must have arrived at a stage of sophistication. This cannot be forced. Even within the same discipline there are great differences in the degree of preparedness to collaborate with areas of neighboring disciplines. Interdisciplinary research cannot be undertaken until and unless there is a feeling of need for help from outside one's own discipline.

4. Interdisciplinary Research Requires Collaboration in Use of Concepts; and Sharing of Work Tasks With Each Disciplinary Researcher Using the Appropriate Research Techniques:

An interdisciplinary team is a group of persons who are trained in the use of different tools and concepts, among whom there is an organized division of labor around a common problem, with each member using his own tools, with continuous intercommunication and re-examination of postulates in terms of the limitations provided by the work of the other members, and often with group responsibility for the final product.

…For research to be considered interdisciplinary there must be integration of concepts. Without some integration, the situation is similar to having occasional meetings with people in other disciplines, or even to just reading about what they are doing. One is influenced to some extent by this kind of interdisciplinary exposure, but more than this is needed for a project to be considered interdisciplinary.

Difficulties due to disciplinary orthodoxy appear to be most severe in academia as brought out clearly by the following discussion related to interdisciplinary research on environmental quality:*

> It will not be easy to begin new problem-focused programs at universities, despite the need for trained professionals and the seriousness of the problems, Dr. J.Kenneth Hare, Professor of Geography at the University of Toronto and former President of the University of British Columbia, commented on these difficulties in an open letter:
>
> "Let me start, then, with the question of environmental studies in a modern University. We all know the conservative quality of such places, where nothing can easily be done for either the first or the last time. The status quo is defended in depth by the vested interest of a large number of able people. Among these interests are those of the traditional departments and the largely analytical disciplines they profess. Also strong are the numerous special institutes and centers that have got started in spite of the resistance of the departments. When we propose to start up a broad spectrum, synthesizing effort like environmental studies we run fulltilt into all these vested interests.

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* John S.Steinhart and Stacie Cherniack— "The Universities and Environmental Quality—Commitment to Problem Focussed Education." A Report to the President's Environmental Quality Council, Office of Science and Technology, September 1969.

> "We also bang ourselves against the clan-spirit of the traditional faculty groupings. Humanists, social scientists, natural scientists, and professionals like lawyers and engineers may fight like cats within the clan, but they close ranks and hitch up their kilts when someone questions their loyalties. Environmental studies have to involve many of these clans, which are not used to combining in the way required. If we suggest, as I do, that some of them—notably the humanists—may be utterly transformed by such combinations we alarm the timid and anger the Tories among them.
>
> "But the greatest hazard in our path is inherent in Lyndon Johnson's acid query "Therefore, what?" which he threw at a group of professors who had just briefed him on the Middle Eastern situation. The political interest in the environment demands proposals for action—on all time scales, from the immediate assault on pollution problems and other festering sores of today, to the long-term reconstruction of society in a better relation with environment. At present we are not equipped to make such proposals. We are not action-oriented and on every campus there is a dead-weight of opinion that regards action-oriented programs as hostile to the academic life…
>
> "I must also stress the incompetence of the established disciplines to tackle society's real problem. What we mean by a discipline is an agreed tested body of method—usually analytical—that we bring to bear on problems of our own choosing. The essence of our thinking is that we cannot tackle problems that don't fit the competence of our own discipline. It's true that we constantly try to enlarge that competence. Confronted with a new problem, we spare no effort to improve our methods. But if we don't succeed, we don't tackle the problem, and we tend to condemn colleagues who try."

Lessons for Interdisciplinary Research

As discussed earlier the coupling between disciplines can range from loose to tight, i.e.,

1. Research workers in different disciplines make a parallel study of various aspects of a single problem and submit separate reports; thanks to this juxtaposition, it is hoped that further light will be shed on the problem under consideration. —Multidisciplinary, loosely-coupled mode.
2. Research workers in different disciplines tackle the same problem simultaneously and synchronize their efforts, exchange findings, and draft separate reports, which will be prefaced by a joint report attempting to integrate all these findings; in this instance what is sought is some degree of convergence, if not through the investigation, then at least in the comparison of findings.
3. Research workers tackle a single problem together, compare their working hypotheses, make a critical assessment of each other's methods and draft a final joint report. —Interdisciplinary, tightly-coupled mode.

There appear to be certain characteristics of close collaboration:

A. From the standpoint of the research problem

1. Focus on a single clearly defined problem.
2. Problem definition determined by demands of problem rather than by disciplinary or individual interests.
3. Formulation of the research problem in such a way that all participants can contribute to its solution.
4. Existence of collaborative potential as a result of previous work on the problem by more than one discipline.

B. From the standpoint of theory

1. Acceptance of a unified over-all theory.
2. Acceptance of a common set of hypotheses and assumptions.
3. Agreement on definition of common concepts.
4. Agreement on operational definitions.

C. From the standpoint of methodology

1. Utilization of resources of all relevant disciplines in exploring possible methodologies.
2. Team agreement on most appropriate methodology, including research procedures, relevant variables to be measured or controlled, and methods to be used.

D. From the standpoint of group functioning

1. Team members selected on basis of their ability to contribute to research objectives.
2. Approximate equality of influence exerted by the representatives of one discipline on another.
3. Acceptance of leadership regardless of disciplines from which leader and researchers come.
4. Flexibility of roles.
5. Development and use of a common language.
6. Free communication among all team members.

7. Free interchange of information about the research, with mechanics for facilitating such interchange when necessary.
8. Sharing of suggestions, ideas, and data among members from different disciplines.
9. Participation of all team members in joint planning of each step of the research.
10. Reciprocal teaching and learning among team members—a continuous learning process.
11. Problem-centered rather than discipline- or individual-centered team activity.
12. Minimum influence on research plans and operations exerted from outside the research team.
13. Willingness of participants to subordinate own methods and interests to achieve project aims.
14. Publication of research reports by the group as a whole, rather than by individual members.

Some of these manifestations of close collaboration will be found to some degree in any project. A few projects where the collaboration is very close appear to contain most of them.

Strengths and Weaknesses in Interdisciplinary Research

The interdisciplinary mode is not a universal panacea. While it is essential for many achievements in complex technology, it has its weaknesses as well as its strengths. Some of these are listed:

Weaknesses and dangers;

a) As teams become larger, originality is apt to be stifled.
b) Individual freedom is restricted through the coordination and organization necessary in group research.
c) Interpersonal difficulties are more likely on larger teams.
d) Interdisciplinary team research can be expensive.
e) When an interdisciplinary team is utilized unnecessarily, resources are spent that could be used more effectively.

f) Closely related to the large investment of money and personnel often required in interdisciplinary research are the pressures for demonstrable results.
g) Interdisciplinary research requires more time in communication, time which might be spent more profitably on the research itself.
h) As teams become larger, more time is needed for administration.
i) The circumstances under which interdisciplinary research is conducted may be distracting.

On the positive side:

a) A team of investigators can tackle larger problems than they can individually.
b) Interdisciplinary research generally gives a broader outlook, opens new horizons, and stimulates more people than individual research.
c) The collaborative experience of interdisciplinary research is more than an additive process, the end result more than the sum total of what each of the disciplines could have achieved independently.
d) One of the most important aspects of interdisciplinary work is the fruitfulness of the challenges from one part of the group in stimulating others to mobilize their resources.
e) Interdisciplinary research broadens understanding through having to translate concepts and approaches between disciplines.
f) Interdisciplinary research illuminates borderline areas and enables one to examine problems lying between disciplines that had previously been ignored by the single disciplines.
g) Interdisciplinary work is advocated enthusiastically by some because of the hope and belief that, by requiring reformulation in translatable terms, it will result in an integrated set of constructs and may even produce a new theoretical framework and a new discipline.
h) Interdisciplinary research facilitates the creation of situations that may result in new and productive combinations.
i) An interdisciplinary approach is valuable in contributing specific techniques and skills from various disciplines to each other.
j) The use of specialists in different fields provides a short cut to information.

k) Interdisciplinary research can be a valuable learning experience that can be utilized effectively for training purposes.

Many of the pitfalls and problems of interdisciplinary team research can be minimized or avoided by recognizing them in advance and guarding against them. Interdisciplinary research should never be conducted for the sake of being interdisciplinary. But many of the complex problems facing the investigator require the concerted attack of several disciplines. When used appropriately, the values of interdisciplinary research far outweigh its disadvantages and it should make increasing contributions toward understanding and solving some of the important problems of today.