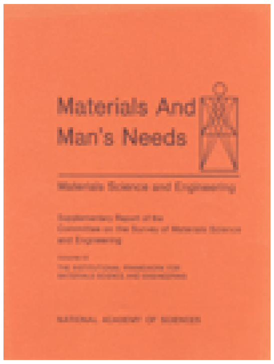

Materials and Man's Needs: Materials Science and Engineering -- Volume III, The Institutional Framework for Materials Science and Engineering

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

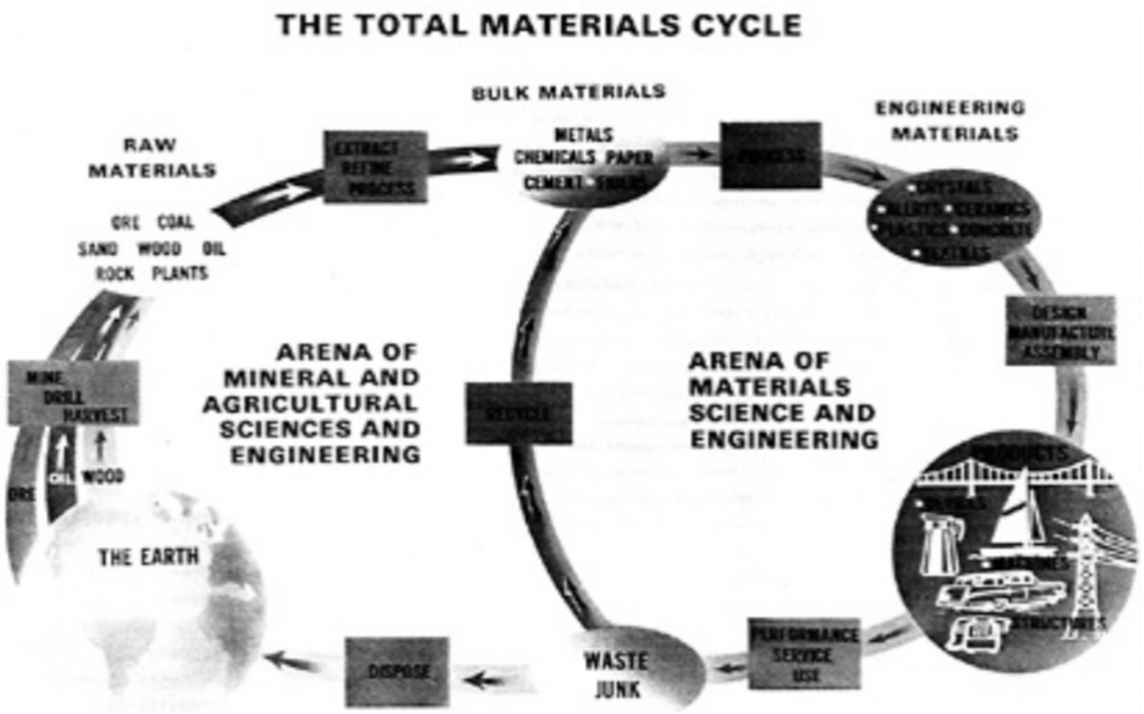
MATERIALS AND MAN'S NEEDS

MATERIALS SCIENCE AND ENGINEERING

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

VOLUME III
THE INSTITUTIONAL FRAMEWORK FOR MATERIALS SCIENCE AND ENGINEERING

NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D.C. 1975


THE TOTAL MATERIALS CYCLE
BULK MATERIALS
ENGINEERING MATERIALS
RAW MATERIALS
EXTRACT REFINE PROCESS
METALS CHEMICALS PAPER CEMENT FIBERS
PROCESS
CRYSTALS ALLOYS CERAMICS PLASTICS CONCRETE TEXTILES
ORE COAL SAND WOOD OIL ROCK PLANTS
DESIGN MANUFACTURE ASSEMBLY
ARENA OF MINERAL AND AGRICULTURAL SCIENCES AND ENGINEERING
RECYCLE
ARENA OF MATERIALS SCIENCE AND ENGINEERING
MINE DRILL HARVEST
PRODUCTS
DEVICES
MACHINES
STRUCTURES
ORE
OIL
WOOD
THE EARTH
DISPOSE
WASTE JUNK
PERFORMANCE SERVICE USE

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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. The 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

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
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CHAPTER 7

INDUSTRIAL, GOVERNMENTAL, ACADEMIC, AND PROFESSIONAL ACTIVITIES IN MATERIALS SCIENCE AND ENGINEERING*

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* This chapter represents the work of COSMAT Panel III, chaired by Walter R. Hibbard, and its committees chaired by Paul F.Chenea (Industry), Paul Shewmon (Government), Rustum Roy (Education), and Donald J.Blickwede (Professional Activities and Manpower). In addition, important information inputs were provided by the COSMAT Data and Information Panel, chaired by Robert I.Jaffee, and by many university department heads and materials research center directors. Numerous colleagues in industry helped in drafting the descriptions of materials activities in several industries. The various sections of this chapter were brought together by S.Victor Radcliffe.

CHAPTER 7

INDUSTRIAL, GOVERNMENTAL, ACADEMIC, AND PROFESSIONAL ACTIVITIES IN MATERIALS SCIENCE AND ENGINEERING

INTRODUCTION

The United States, with about one-twentieth of the world's population, consumes more than one-third of the world's mineral resources. However, although the American people have become accustomed to the ready availability of a great variety and quantity of material goods, the mineral-resource base from which many of the materials are derived is changing in character and accessibility. Private industry, our society's institution for providing these material goods, has developed a remarkably successful system to keep pace with the ever-growing product demand. World trade and improved technology are both parts of this system. Thus, the U.S. must export products and/or resources to pay for raw material imports and, through continued scientific and technological improvements in materials production and application, compete effectively in world product markets.

About one-fifth of the U.S. gross national product originates in the extraction, refining, processing, and forming of materials other than food and fuel. Thus, the translation of raw materials into finished goods is a large and significant economic activity. Nevertheless, the public is not normally perceptive of the materials because of their ubiquitous nature and the fact that they are seldom products in their own right.

All materials pass through a number of stages from their extraction to utilization. At each stage, economic value is added and costs are incurred to pay for energy, production manpower, research manpower, and administration. In addition, costs are incurred in post-use disposal and recycling. The institution generally employed in our society for implementing this utilization of materials is private industry. Competing in the marketplace under ground rules established by society through its governmental bodies, private industry attempts to minimize the cost of materials utilization to produce quality goods that satisfy its customers and to provide a reasonable return on investment to its owners.

As discussed in earlier chapters, the concept of the materials cycle, or the physical flow of materials, is very useful for perceiving the interrelationships of the various stages of extraction, conversion, processing, fabrication or assembly, product utilization, and scrap disposal or recycling. The general characteristics of the materials flows, including related energy and waste flows, that would have to be taken into account in a quantitative model are indicated in Figure 2.3 of Chapter 2.*

Materials are produced in commodity-oriented industries such as rubber, plastics, metals, glass, ceramics, cement, timber, and chemicals. Materials are consumed in product-oriented industries such as transportation, electronics, containers, lighting, and construction. The ultimate user, society itself, is concerned principally with the cost, performance, and functional value of products, and is only incidentally knowledgeable in the materials involved in their manufacture. Because of future prospects regarding changes in the character of the sources of traditional materials and the increasing utility of newer materials such as aluminum, electronic materials, and synthetic polymers—and the increasing potential for designing materials to provide desired engineering performance—it is important that appropriate attention be given to the continued development of the science and technology of materials. This evolving field, which already affects almost all of the capital and consumer goods that we are familiar with, promises to have a worthwhile influence on this nation's future economic, aesthetic, and social well-being.

Regarding the existing relations between resource supplies and world trade, important changes are well underway and unmistakable. For example, a 1970 analysis[1] reports that the U.S. has "rapidly deteriorating, and by now large," deficits in trade with minerals and raw materials, and with manufactured materials such as steel, textiles, and nonferrous metals. In addition, exports of finished products which could help to offset these deficiencies, are also in a rapidly deteriorating position. Furthermore, we are faced with the same question whether the concern is with the depletion of the world-wide reserves or the deficiency of indigenous resources in the U.S. Today we require a greater supply of materials than at any previous time in our history. Our national overall annual requirements for materials are expected to continue to grow by several percent each year through the end of the century. Figure 7.1 illustrates current supply change and use patterns for several major materials, and Table 7.1 summarizes the U.S. per capita consumption. The U.S. already depends on foreign supplies for the majority of its tungsten, chromium, manganese, platinum, mica, bauxite, cobalt, nickel, asbestos, and about a dozen other mineral commodities. In addition, current engineering applications of zinc, nickel, copper, cobalt, lead, tin, and the precious metals are cutting into the world's proven reserves.

That technological innovation can assist industry to keep pace with growing demand for materials by offsetting some of the above constraints is illustrated by the case of copper. At the turn of the century, typical ore grades from copper mines were about 5% copper. Yet today, the average grade of copper deposits mined in the U.S. is less than one percent copper—about 14 pounds per ton. Although the available copper has decreased drastically in grade, improvements in mineral and metallurgical practices still allow production of copper at a reasonable price. Indeed, there is potential

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* Chapter 2, Volume I, of this Series.

[1] Michael Boretsky, "Concerns About the Present Trade Position in International Trade," Technology and International Trade, NAE (1970) pp, 36 and 48.

FIGURE 7.1 CHANGES IN U.S. SUPPLY AND USE OF MAJOR INDUSTRIAL MATERIALS (FROM FIRST ANUAL REPORT TO CONGRESS OF THE SECRETARY OF THE U.S DEPARTMENT OF INTERIOR, MARCH 1972)

FIGURE 7.1a U.S. SUPPLIES AND USES OF IRON

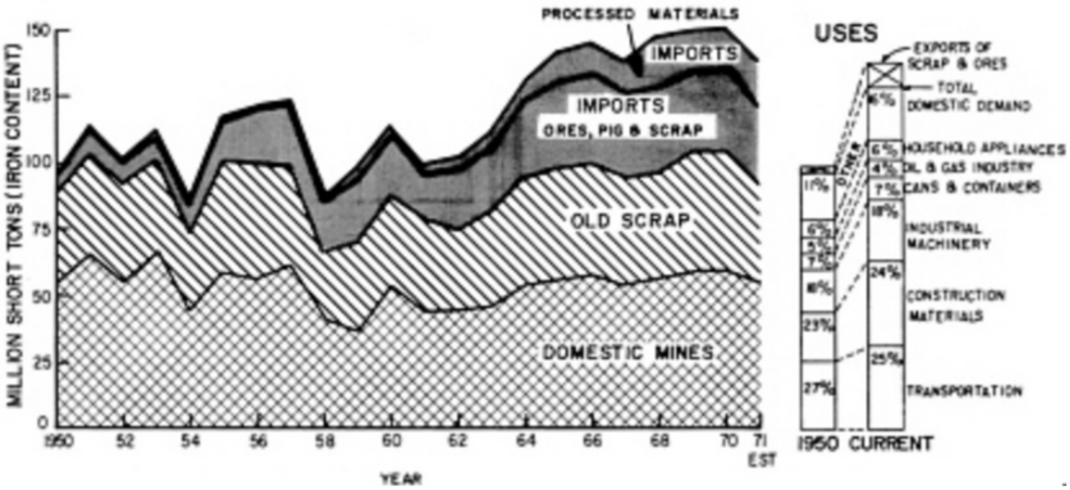

FIGURE 7.1b U.S. SUPPLIES AND USES OF ALUMINUM, COPPER, ZINC, AND LEAD

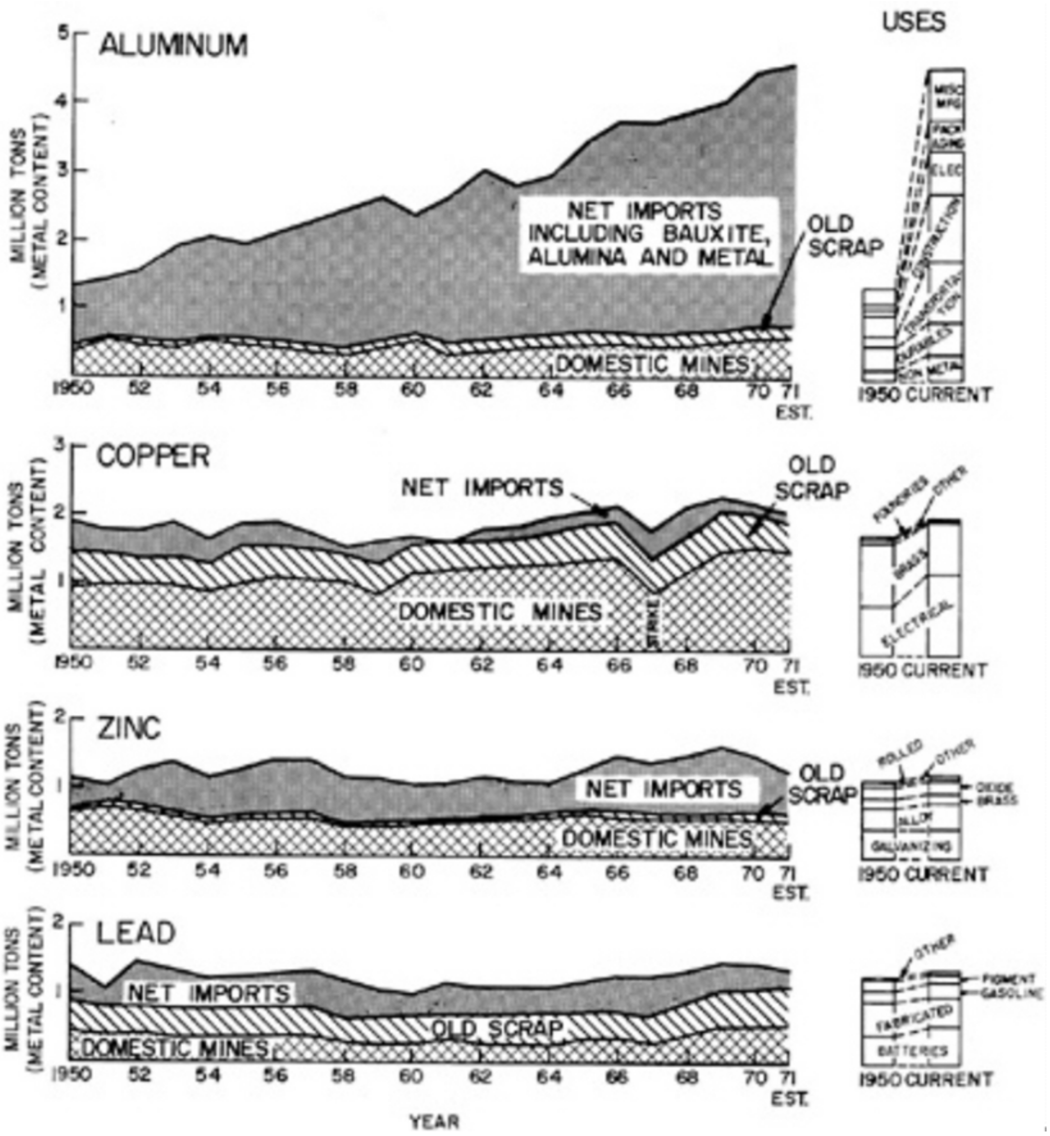

FIGURE 7.1c U.S. SUPPLIES AND USES OF PLASTICS

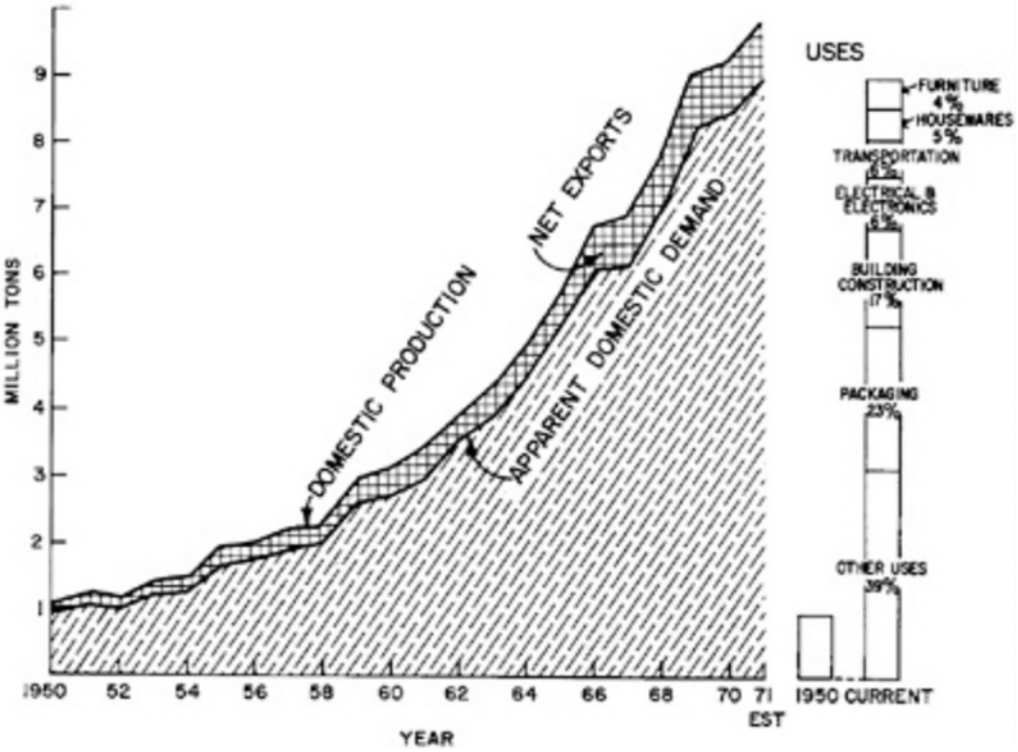

TABLE 7.1 Annual Requirements for Principal Primary Materials Used in the United States (Pounds per capita, 1972)

A. Nonmetallic Inorganic Materials:		
Sand and gravel	9000	
Stone	8500	
Cement	800	
Clays	600	
Salt	450	
Other	1200	20550
B. Metals:		
Iron and steel	1200	
Aluminum	50	
Copper	25	
Lead	15	
Zinc	15	
Other	35	1340
C. Natural Organic Materials:		
Forest products	2750	
Natural fibers and oils	50	
Natural rubber	10	2810
D. Synthetic Organic Materials:		
Synthetic polymers	116	
(including rubber)		116
	TOTAL	24816

(Equivalent total for entire U.S. population = 2.57 billion short tons.)

technology that may make it feasible to mine down to 4 pounds per ton.

While advances in extraction technology are capable of easing our dependence on foreign sources of raw materials, improved technology in other stages of the materials cycle could enhance the effectiveness of materials utilization and hence relieve pressure on new supply. Figure 2.4 of Chapter 2*illustrates some of the social and technical pressures that operate at various stages of the economic utilization of materials. A strong materials technology is a key element in permitting industry to be responsive to these pressures and yet still produce goods at reasonable cost.

MATERIALS IN INDUSTRY

Consideration was directed in Chapter 2 to the changing world conditions in which the institutions of the materials field—in industry, government, and universities—must function. Attention is now given to illustrating in more detail the principal features of industrial areas which operate to meet man’s present and future needs for materials to perform desired functions in goods and services. The features are highlighted by examining three key materials-producing industries (metals, inorganic nonmetals, and plastics), and five industries that are major users of materials (electronics, lighting, containers, automobile, and building). Finally, in the closing part of this section, the important role of materials standards and specifications is reviewed.

Before discussing the individual industries, it is useful to view their relative efforts devoted to process and product improvement and innovation through their R&D activities. Although accurate information for these industries is unavailable, some comparison with the full range of U.S. manufacturing industry is given by data in Tables 2.19, 2.20, and 2.21 of Chapter 2. The industries listed in these tables are the Standard Industry Classification (SIC) sectors often used in national statistics. While these sectors do not always exactly match the industries to be discussed here, they are close enough to indicate two important points. The first is that the metals and inorganic-nonmetals producing industries—like most primary product industries—show R&D expenditures that are considerably smaller in absolute terms than the four industry sectors leading the list, and they also stand lower as a proportion of the industry sales revenue. The second point is that, unlike the leading industries (except for chemicals, in which the plastics industry would be included), these materials-producing industries essentially fund their own R&D and receive little federal R&D support. While presently available national statistics do not permit a more detailed analysis of industrial materials R&D, Table 2.21 indicates that total R&D in the materials-producing industries is somewhat more than one billion dollars, almost all of which is supported by industrial funds. In addition, a substantial amount of R&D is carried out in the materials-using industries, although the actual dollar value has not been ascertained.

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* Tables and Figures referred to on this page can be found in Chapter 2, Volume I of this Series.

Principal Materials-Producing Industries

Metals Industry

Table 7.2 shows the expected demand for metals over the next 15 years. Iron and steel continue to be the leading metals industry in scale and value and a significant indicator of the nation's economic wellbeing. In terms of both quantity and value, aluminum and copper are the principal metals in the nonferrous group. They are followed by 44 other elements, ranging from the precious metals, gold, silver, and platinum, with very high unit values but relatively small volume usage, through the industrial metals such as lead, zinc, mercury, and the light metals such as magnesium and titanium.

Major applications and future growth areas are strongly oriented toward consumer goods, transportation and construction industries, and the generation and use of electrical energy. Continuing increases in the real costs of production and an anticipated growth in utilization are the principal factors contributing to an increase in domestic demand for the nonferrous commodities (from about 15% of the 1970 value for all mineral commodities up to about 18% of the total in 1985).

Industry Structure: A large part of the metals industry is concentrated, i.e. is characterized by large vertically integrated companies which are able to optimize both their raw materials sources and their markets. Major factors leading to this structure are the worldwide occurrences of ores and raw materials and the complex coproduct-byproduct relationships. Thus, dispersion of raw material sources encourages formation of multinational companies, and broad-based markets results from the production of the many metals of interrelated occurrence. The latter is especially true in the base metals. The significance of imports and import sources to the U.S. is illustrated in Table 7.3. Similarly, Table 7.4 shows the metal byproducts recovered in the processing of ores for the major metal content.

A tendency toward horizontal integration along functional lines has developed during the last two decades. For example, major copper-producing companies have expanded their operations to include production of primary aluminum. Primary aluminum producers are likely to become involved in primary copper production within the next decade. Because of the many common markets shared by the light metals, aluminum, magnesium, and titanium, the production and processing of two or more of these elements by single firms will tend to expand during the remainder of this century. The similarities in uses and properties of titanium and alloys of iron have already led steel companies to invest in primary production facilities for both of these elements. The following paragraphs illustrate these various structural features for specific metals industries.

In iron and steel, an estimated 60% of domestic iron ore production was accounted for by nine steel companies; these same organizations produced about 75% of the nation's crude steel in 1970. The two largest U.S. companies produced 34% of the domestic iron ore, 40% of the crude steel, and also accounted for the bulk of U.S. imports of iron ore from mines in Canada, Venezuela, Liberia, and Chile.

TABLE 7.2 U.S. Demand for Selected Primary Metals, 1970 and 1985*

		Demand		Growth, percent	
Metal	Units	1970	1985	Annual Compound	Total 1970–1985
Ferrous:					
Iron	Million S.T.	84	113	2.0	135
Manganese	Thousand S.T.	1,327	1,770	1.9	135
Chromium	Thousand S.T.	462	700	2.8	150
Vanadium	S.T.	7,066	14,700	5.0	210
Nickel	Thousand lb.	311,400	492,200	3.1	160
Molybdenum	Thousand lb.	49,104	96,500	4.6	195
Tungsten	Thousand lb.	16,200	34,200	5.1	210
Nonferrous:					
Aluminum	Thousand S.T.	3,951	11,500	7.4	290
Copper	Thousand S.T.	1,572	2,900	4.2	185
Zinc	Thousand S.T.	1,302	1,820	2.3	140
Lead	Thousand S.T.	829	1,100	1.8	130
Magnesium**	Thousand S.T.	96	235	6.1	245
Tin	Thousand L.T.	53	70	1.9	130
Titanium**	Thousand S.T.	24	65	6.9	270
Mercury	Thousand fl. (flasks)	54	66	1.3	120
Silver	Thousand Troy oz.	73,100	124,000	3.6	170
Gold	Thousand Troy oz.	6,147	9,200	2.7	150
Platinum	Thousand Troy oz.	407	634	3.0	155

* From First Annual Report of Secretary of the U.S. Department of Interior, March 1972.

** Metal only, all others include both metallic and nonmetallic applications.

TABLE 7.3 U.S. Imports by Source and as Percent of Apparent Consumption, 1970

Metal	Imports /Consumption, percent	Major Import Source
Ferrous:		
Iron	33	Canada, Venezuela
Manganese	82	Brazil, Gabon, Rep. South Africa, India
Chromium	84	U.S.S.R., Rep. South Africa, Turkey, Philippines
Vanadium	29	Rep. South Africa, U.S.S.R., Chile
Nickel	75	Canada, Norway
Molybdenum	Nil	
Tungsten	8	Canada, Peru, Mexico
Nonferrous:		
Aluminum	118	Jamaica, Surinam, Canada, Australia
Copper	19	Chile, Peru, Canada
Zinc	51	Canada, Mexico, Peru
Lead	27	Canada, Australia, Peru, Mexico
Magnesium*	3	Canada
Tin	76	Malaysia, Thailand
Titanium*	40	Japan, U.S.S.R.
Mercury	35	Canada, Spain
Silver	48	Canada, Peru, Mexico, Honduras
Gold	47	Canada, Switzerland, United Kingdom, Nicaragua
Platinum	139	United Kingdom, Rep. South Africa, Japan, U.S.S.R.

* Metal only, all others include both metallic and nonmetallic applications.

TABLE 7.4 Byproduct Relationships for Selected Metals, 1970

Ore	100 Percent of Total Output		Less Than 100 Percent of Total Output	
Iron	Cobalt		Manganese	Gold
			Copper	Silver
Aluminum			Gallium	
Copper	Arsenic	Selenium	Palladium	Platinum
	Rhenium		Tellurium	Nickel
			Gold	Zinc
			Silver	Iron
			Molybdenum	Lead
Lead	Bismuth		Antimony	Gold
			Zinc	Copper
			Silver	Manganese
			Tellurium	
Zinc	Cadmium	Indium	Lead	Gold
	Germanium	Thallium	Silver	Mercury
			Manganese	Copper
			Gallium	

In aluminum, four of the 12 domestic firms producing primary aluminum and representing about 72% of total productive capacity in 1970 were vertically integrated from mining through production of semifabricated shapes. Two of the remaining firms were owned or associated with foreign integrated firms. Others produced aluminum from purchased bauxite or alumina, and all had facilities for producing semifabricated shapes. Worldwide, the aluminum industry is vertically integrated with very few exceptions. Six companies control or influence (by majority or minority interests) over 75% of the world productive capacity for primary aluminum.

In copper, 25 mines accounted for 93% of the U.S. copper output in 1970. The five largest produced 42%, and three companies accounted for a little more than half of the domestic mine production. Virtually all copper ore continued to be treated at concentrators near the mines. Concentrates were processed at 17 smelters—eight in Arizona and one each in Utah, Michigan, Montana, Nevada, New Mexico, Tennessee, Texas, New Jersey, and Washington. Copper smelting capacity in the U.S. in 1970 totaled 9.2 million tons of charge, equivalent to about 1.9 million tons of smelter product; four companies constituted nearly 80% of the capacity. Refinery capacity totaled 2.7 million tons of which 89% was electrolytic refining capacity and 11% was fire-refining (including Lake copper) capacity.

Many large domestic copper producers, through subsidiaries or stock holdings, operate or control foreign copper-producing properties in Canada, Mexico, Peru, the Republic of South Africa, and Zambia. In addition to copper and the usual byproducts, some of these companies are also major producers of aluminum, cadmium, chromium, germanium, lead, titanium, uranium, vanadium, zinc, asbestos, fluorspar, precious metals, and liquid and solid fuels.

In lead, domestic companies accounted for 61% of the lead mined and practically all of the primary smelter production in 1970. These large companies are vertically integrated (from mine to refined lead) and are also horizontally integrated with other base-metal production. Other companies in the industry are essentially mine operators utilizing, to a varying degree, custom plants for concentration, smelting, and refining. The leading 25 mines accounted for over 95%, and the leading 5 mines for 64% of the total domestic primary production in 1970. Four states produced 97% of the total domestic production; Missouri contributed 74%; Idaho, 11%; Utah, 8%; and Colorado, 4%.

In zinc, companies prominent in the U.S. zinc mining or smelting industry likewise have substantial interests in important mines and related operations in foreign countries. Conversely, certain foreign firms have significant interests in segments of the U.S. zinc industry. In 1970, the primary zinc producing industry in the U.S. was dominated by six large vertically integrated firms that controlled mines, smelters, and/or refineries. These six, along with one company having only an electrolytic refiner, accounted for 90% of the slab zinc produced domestically. Nine prominent U.S. companies have substantial interests in foreign zinc activities. Holdings are in properties located in Canada, Mexico, Argentina, Peru, Australia, and southwestern Africa.

Recycling of Metals: Published statistics on the reuse of metal wastes through recycling are frequently confusing in that they often fail to distinguish between scrap recovered from the materials-producing or using industry (home or prompt industrial scrap) and that derived from post-consumer wastes (old scrap) or imports. Figure 7.2, which is based on the aluminum industry, illustrates the origins of these types of scrap at the different stages of metal flow through the materials system. Clear delineation of these separate scrap sources is especially important in the light of current material concerns about the management of waste or residual flows for purposes of environmental protection and materials conservation.

Table 7.5 shows the current levels of total scrap recovered in the U.S. for the major metals. These data indicate the modest recovery of secondary aluminum and zinc (17% of consumption) compared with that for secondary copper (i.e. copper recovered from scrap as metal, as alloys without separation of the copper, or as compounds). Both the intrinsic value and long-established recovery technologies contribute to the higher rate for copper. The largest amount recovered as metal is reclaimed by the primary copper producers as electrolytic copper. However, alloyed copper, principally brass and bronze, comprises more than 50% of the total recovery and is prepared by secondary smelting and casting processes.

Lead, like copper, has a high annual rate of recovery—amounting to 44% of consumption. Half of the lead consumed each year is added to the lead-in-use resource, i.e. becomes available for recycling. In contrast to copper and lead, only 17% of zinc supply comes from scrap. Most of the zinc from old scrap (such as manufactured items discarded because of wear, damage, or obsolescence) is recovered in the form of die-castings, engravers' plates, brass, and bronze, but this represents less than 5% of the total supply. New scrap, principally zinc-base and copper-base alloys from manufacturers, and drosses, from molten galvanizing and die-casting pots, contribute 10–15%. The large usage of zinc in galvanizing and in compounds (such as paints) where the zinc is lost is a major obstacle to improved recycling of zinc.

Over the last 30 years, total annual consumption of ferrous scrap by the iron and steel industry has been close to a 1:1 ratio with virgin pig iron. Home scrap accounts for well over 60% of the scrap used in the steelmaking furnaces; less than 15% is prompt scrap, and the balance is obsolete material.

Currently, the development of sophisticated processing and materials-handling equipment is revolutionizing major areas of the purchased-scrap industry. For example, giant shredders, or fragmentizers, with magnetic separators and pneumatic cleaning devices can convert up to 1,000 automobile bodies per day into scrap (i.e. at a rate of less than 30 seconds each). The combined national capacity of about 70 super-shredders and small-to-medium sized shredders in operation in 1968 was described as over 6 million tons, about equalling the tonnage of cars junked that year. Advances in balers, automatic shears, and conveyors contributed to the mechanization trend. Improved quality-control equipment permits the processor to deliver scrap material to more exacting specifications. In contrast with such changes, economically viable technologies for metals recovery from another major source—urban wastes—remain to be developed.

Environmental Considerations: Environmental-quality requirements introduced over the past decade have significant impacts on the mineral industry. For instance, fumes from zinc smelters may contain cadmium, those from copper smelters may contain arsenic, and both operations generate sulfur dioxide.

FIGURE 7.2 DIAGRAMATIC FLOW OF INDUSTRIAL AND POST-CONSUMER SCRAP METAL

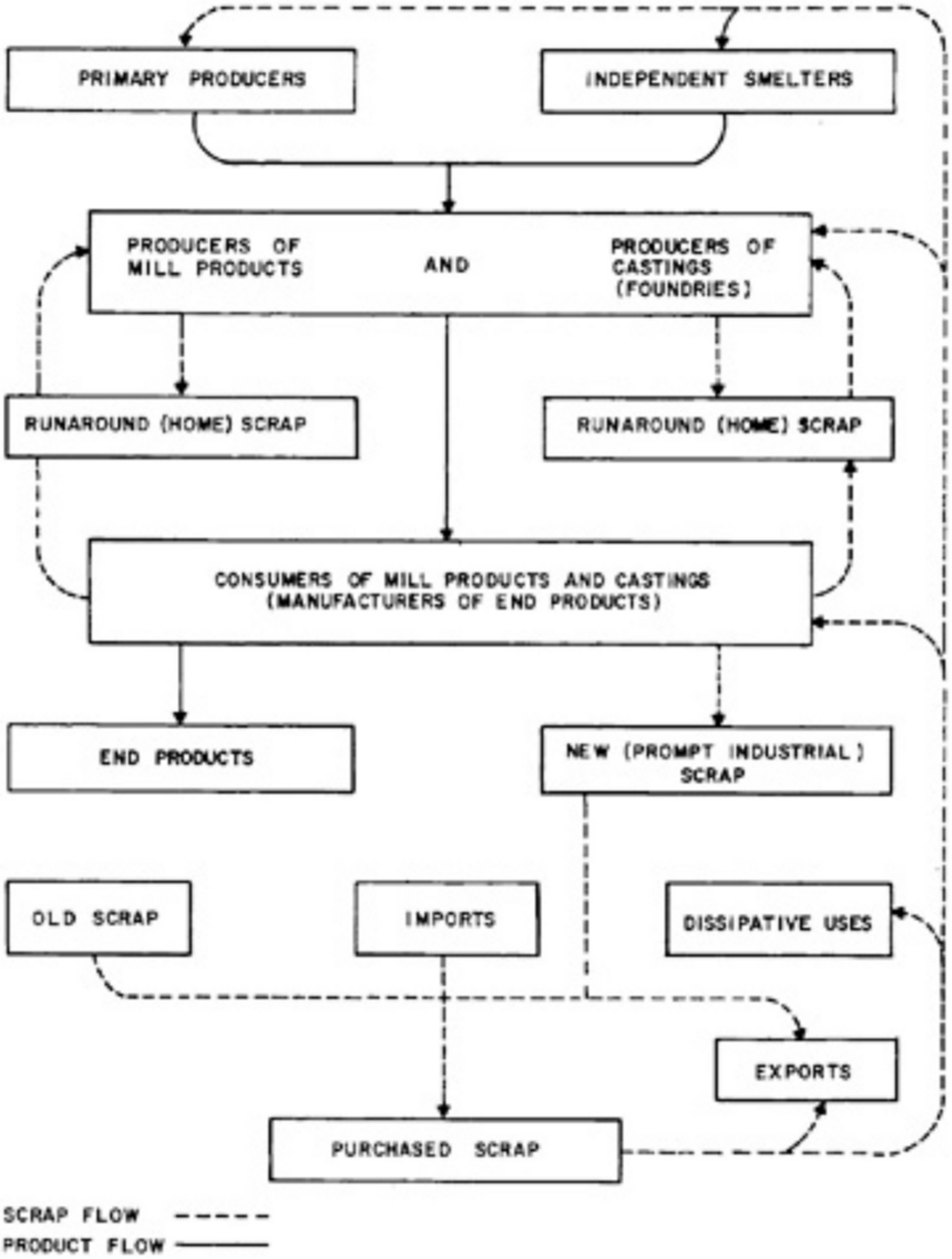

TABLE 7.5 Recovery of Metals from Scrap as Related to Total Consumption, 1970 (Thousand Short Tons)

Metal	Secondary Recovery	Total Consumption	A\B, percent
Aluminum	781	4,519	17
Copper	1,248	2,779	45
Iron	44,700	116,900	38
Lead	597	1,360	44
Zinc	260	1,572	17

To control such pollutants within acceptance limits requires add-on equipment to remove them or even changes in the technology of the extraction processes themselves. Thus, in order to assist in minimizing the release of such pollutants, there is a need to improve the methods of recovery of “associated” metals (e.g. bismuth antimony, rhenium, cadmium, indium, and others) that occur with copper, lead, and zinc ores. Ordinarily, these associated metals are present in such small amounts that they are disregarded in commercial smelting operations.

In addition to problems in processing, the actual utilization of some metals is being reduced because of environmental concern. Examples are the curtailed demand for mercury and the decrease in the demand for lead as automobile fuel is switched away from leaded gasoline. Conversely, demand for other metals is likely to increase due to construction requirements for pollution-control equipment. One specific example is the expected increase in demand for platinum in automobile catalytic mufflers to meet the requirements of the Clean Air Act of 1970. Correspondingly, petroleum refineries may need more platinum for catalysts as demand for lead-free gasoline is increased.

The following summarizes the capital expenditures expected in the various metal industries to comply with environmental regulations over the next several years. To control air and water pollution associated with the smelting and refining of aluminum, an investment of $935 million will be required for the period 1972 through 1976. Annual costs are estimated to range from $22 million in 1972 to approximately $290 million in 1976. Cost increases per pound of aluminum in 1976 may average $0.020 to $0.032.[2] For copper, control of smelter stack-gas emissions is the most pressing problem facing the U.S. industry. Estimated capital investment for air- and water-pollution controls required of the copper industry between 1972 and 1976 is expected to total $300 million to $690 million, with a most likely estimate of $340 million. Annual costs are estimated to increase from $6 million in 1972 to $95 million in 1976. Per pound of refined copper, these costs would average $0.001 in 1972 and $0.025 in 1976, with a possible high estimate of $0.05 in 1976.[2]

For lead, the total capital expenditure required to control the pollution associated with smelting and refining, might be about $70 million for the 1972 to 1976 period, with annual costs increasing from $1.1 million in 1972 to $20 million in 1976. Costs per pound of lead in 1976 have been estimated at $0.012 to $0.017.[2] However, these studies did not consider the substantial changes in the lead markets that might be caused by other pollution abatement regulations such as those to reduce the lead content of gasoline. For zinc smelting and refining, $62 million of capital expenditures are estimated for the period 1972 to 1976. Annual pollution-control costs may increase from $1.5 million in 1972 to $27 million in 1976, averaging $0.0123 to $0.0267 per pound of zinc, with an expected cost of $0.0135 per pound.[2]

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[2] Charles River Associates Incorporated, Cambridge, Mass. “The Effects of Pollution Control on the Nonferrous Metal Industry,” prepared for the Council on Environmental Quality, December 1971. (released March 1972)

Inorganic Nonmetals Industry

Demand for inorganic nonmetallic materials accounted for 8% of total mineral tonnage in 1950, an estimated 8% in 1971, and is projected to be 11% in 2000. These materials include a wide range of substances, from large-bulk items such as sand, gravel, stone, and clay, through intermediate processed materials such as ceramics, electronic crystals, and synthetic high-hardness abrasives. In general, they are produced in response to near-term demand, and domestic reserves for most major nometallics are large. Domestic mineral production of nonmetallics in 1971 was valued at $5.9 billion. The corresponding variety of materials is shown in Table 7.6. Many are large tonnage items, of initial low value in the unprocessed stage, but acquiring substantial added value in the form of glass, ceramics, chemicals, etc.

Nonmetal mining or industrial-minerals operations tend to be diverse in size and degree of integration. In general, the abundance of these items is such that there is no reclaimed material production. For the most part, the secondary or reclamation segment of the nonmetallic minerals industry is limited to some reclaimed fluorine, diamonds, and abrasives. Pollution-control regulations may force an increase in recycling but high transportation costs are likely to limit the size and market for such operations.

In the following, attention is given to some of the major categories of materials involved in order to illustrate the principal features of the industry. The categories are ceramics, construction materials, fertilizer minerals, and a selection of the other major nonmetallic materials.

Ceramic Materials: The technology of ceramic materials may be divided into two major categories. One branch produces large quantities of relatively simple products which in total play a significant role in the U.S. economy: cement, brick, tile, glass, whiteware, refractories, clay products, etc. The technology of these materials has, in general, kept pace with needs. In recent years, however, the float process for flat glass came from abroad, and glass imports have been sufficiently large to cause some problems for the domestic industry. Another branch of ceramics is more closely allied to the frontiers of materials science, solid-state physics, and solid-state chemistry. This branch has developed the transistor, synthetic diamonds, luminescent phosphors, and high-temperature oxides, carbides, nitrides, borides, etc. Nuclear fuels are an important development of this activity. These specialized materials require the application of scientific thinking and practices, and have resulted in the establishment of whole new industries. However, continued progress in the science of such materials is dependent upon further extensive research of the most fundamental nature and the interchange of information among widely differing scientific disciplines.

Shipments of products from the ceramic industry which totalled some $15 million in 1972 are important inputs into the construction, container, auto, lamp, and electronics industries discussed in other sections of this chapter. In addition, nuclear fuels, refractories, carbon, and graphite are important components of energy supplies, containment, and use. Materials listed in Table 7.7 illustrate the wide variety of essential ceramic products and the industries to which they contribute. Figures 7.3 through 7.6 show the different growth characteristics of some of the principal ceramic materials and products since the early 1960’s.

TABLE 7.6 Nonmetallic Minerals, 1971 (Preliminary Data)* Short Tons

	Supplies		Uses
	Domestic Primary	Imports for Use	Including Government Stockpiling, Industry Stocks, and Exports
Asbestos	132,000	675,000	807,000
Clays	55,000,000	55,000	55,055,000
Corundum	0	0	2,000
Diatomite	537,000	537	537,537
Feldspar	712,000	2,490	714,490
Garnet	18,325	153	18,478
Graphite	**	57,575	**
Gypsum	9,647,000	6,094,000	15,741,000
Kyanite	**	1,343	**
Mica, scrap & flake	119,000	3,640	122,640
Mica, sheet	0	2,833	2,833
Perlite	456,000	0	456,000
Pumice	3,126,000	399,733	3,525,733
Sand & Gravel	987,000,000	715,000	987,715,000
Stone, crushed	820,000,000	3,000,000	823,000,000
Stone, dimension	1,500,000	300,000	1,800,000
Talc	1,053,000	17,381	1,070,381
Vermiculite	277,000	10,000	287,000

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* First Annual Report of the Secretary of Interior, March 1972.

** Withheld to avoid disclosure of company-confidential data.

TABLE 7.7 Ceramic Industry—Total Value of Shipments* (in billions of dollars)

	1972**	1967	1963	1958	1954	1947
Construction Ceramics						
Flat Glass	.732	.611	.549	.385	.371	.224
Cement Hydraulic	1.370	1.247	1.177	1.074	.811	.409
Brick & Structural Clay Tile	.445	.362	.366	.287	.250	.145
Wall & Floor Tile	.198	.161	.165	.136	.097	.041
Structural Clay Products NEC	.196	.153	.160	.135	.111	.076
Vitreous Plumbing Fixtures	.260	.170	.156	.143	.116	.068
Mineral Wool	.504	.454	.392	.241	.157	.073
TOTAL CONSTRUCTION	3.705	3.158	2.965	2.401	1.913	1.036
Consumer Ceramics						
Glass Containers	1.988	1.352	1.004	.862	.635	.422
Pressed & Blown Glass NEC	1.205	.886	.631	.445	.411	.235
Vitreous China Food Utensils	.092	.067	.051	.048	.044	.043
Fine Earthenware Food Utensils	.064	.047	.059	.050	.066	.072
Pottery Products NEC	.107	.096	.096	.079	.055	.039
** Metal Stamped Enameled Products	.183	.126	.090	.080	.066	.050
** Porcelain Enameled Stove Equipment	.137	.095	.079	.067	.056	.036
** Porcelain Enameled Refrigeration Equipment	.212	.147	.122	.066	.048	.028
** Porcelain Enameled Domestic Laundry Parts	.134	.094	.076	.062	.045	.027
** Porcelain Enameled Electrical Appliance Parts	.103	.053	.047	.045	.037	.028
Porcelain Teeth	.014	.013	.012	.014	.013	.011
TOTAL CONSUMER	4.239	2.976	2.267	1.818	1.476	.996

	1972(1)	1967	1963	1958	1954	1947
Industrial Ceramics						
Inorganic Pigments	.610	.561	.480	.412	.372	.278
Aluminum Oxide	.500	.402	.319	.215	.167	.051
Clay Refractories	.317	.246	.192	.164	.136	.042
Porcelain Electrical Supplies	.305	.225	.132	.098	.078	.071
Abrasive Products	.950	.725	.704	.490	.333	.225
Asbestos Insulation	.436	.353	.280	.189	.153	.120
Minerals, Ground & Treated	.337	.281	.204	.219	.149	.090
Nonclay Refractories	.394	.307	.250	.178	.131	.090
Mineral Products, NEC	.148	.100	.096	.059	.055	.030
Carbon & Graphite Products	.330	.296	.227	.155	NA	NA
Nuclear Fuels	.500	.005	NA	NA	NA	NA
TOTAL INDUSTRIAL	4.827	3.501	2.884	2.179	1.574	.997
Electronic Ceramics						
Transistors	.652	.429	.277	.115	NA	NA
Diodes & Rectifiers	.324	.263	.192	.085	NA	NA
Other Semi-Conductors	.218	.186	.092	.080	NA	NA
Ceramic Dielectric Capacitors	.125	.062	.050	.026	NA	NA
Resistors, Non-wire wound	.110	.092	.058	.023	.010	NA
Transducers, Acoustical	.230	.142	.077	.015	.003	NA
Printed Circuit Boards	.012	.006	.009	NA	NA	NA
Ferrite Microwave Components	.021	.017	.011	NA	NA	NA
Ferrite Magnets	.168	.100	.041	NA	NA	NA
TOTAL ELECTRONIC	1.860	1.297	.807	.344	.013	—
GRAND TOTAL—CERAMIC INDUSTRY	14.631	10.932	8.923	6.742	4.976	3.029

* Source of these data is the U.S. Bureau of Census, Census of Manufacturers, except as indicated below.

** Estimated shipments of manufacturers' level by Ceramic Age; 88(1), 1972.

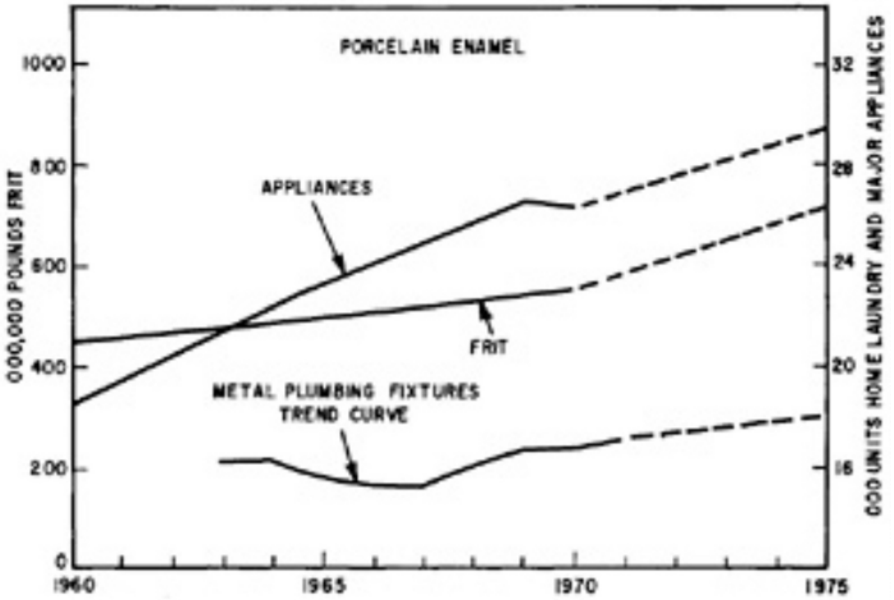


FIGURE 7.3 CONSUMPTION OF PORCELAIN ENAMELS IN THE U.S.

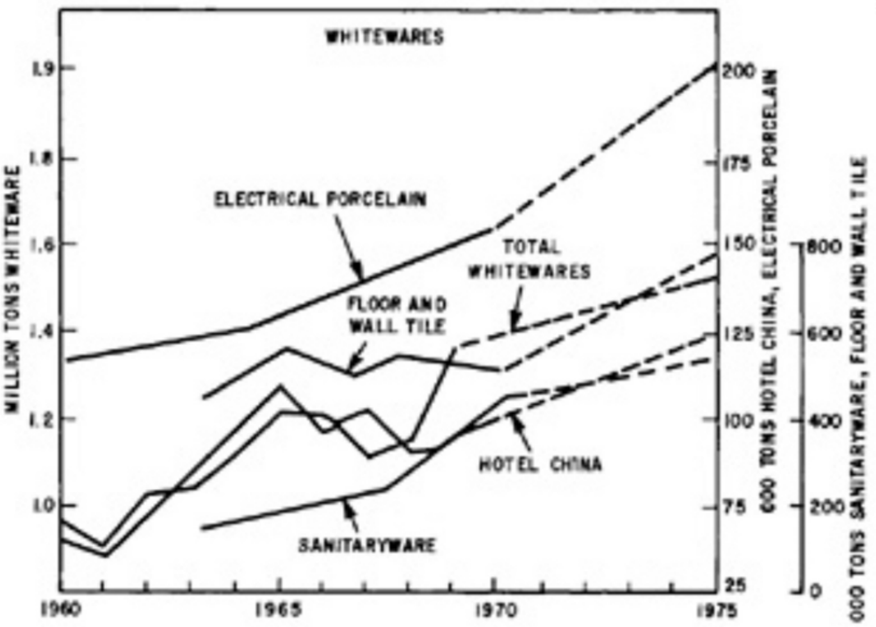


FIGURE 7.4 COMSUMPTION OF WHITEWARES IN THE U.S.

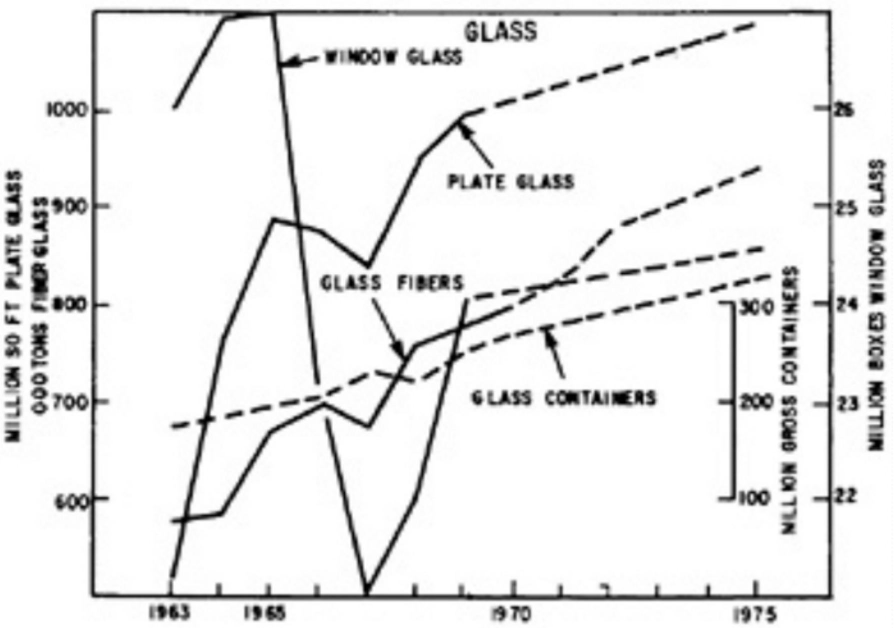


FIGURE 7.5 CONSUMPTION OF GLASS AND GLASS PRODUCTS IN THE U.S.

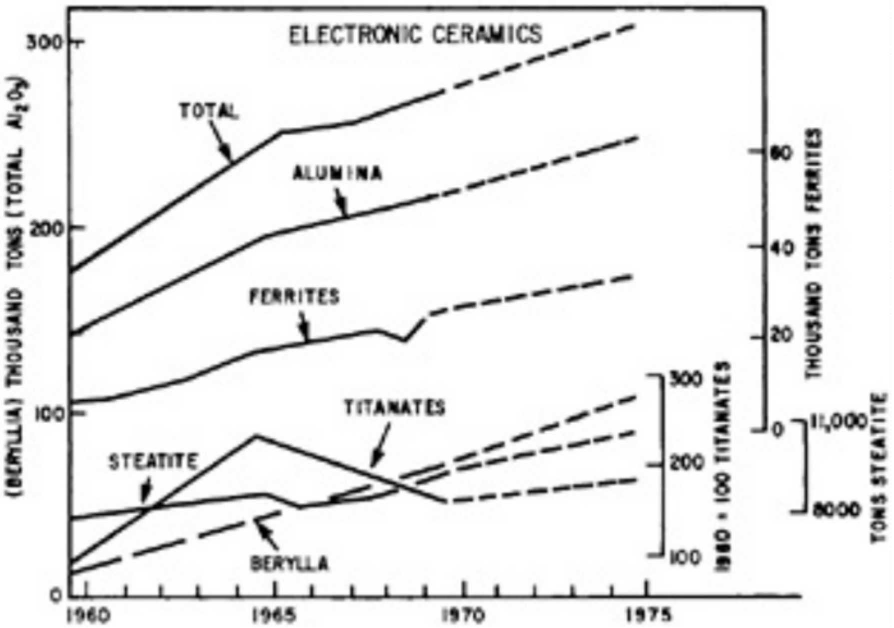


FIGURE 7.6 CONSUMPTION OF ELECTRONIC CERAMICS IN THE U.S.

Construction Materials: Figure 7.7 shows that the use of nonmetallics in construction has more than tripled over the past two decades. These materials are produced almost wholly within the U.S. and imports are negligible. Further, except for the reuse of some old brick, and of building rubble as construction fill, recycling is not a factor. It is apparent that there have been steady and roughly proportionate increases in the use of cement, stone, and sand and gravel; these substances are commonly mixed together in specific proportions to make the heavy construction material for foundations, bridges, buildings, airports, roads, dams, etc. The consumption of clay and gypsum has increased slightly in recent years; clay is used to make a variety of products such as tile, pipe, and ceramics for construction, and gypsum is used to make plaster board which is in wide demand for its insulating and fire-retardant properties.

Fertilizer Materials: Figure 7.8 shows the rise in the U.S. use of the three major fertilizer ingredients—nitrogen, phosphorus, and potassium (N-P-K). The major increase in domestic agricultural productivity since World War II has resulted, in significant degree, from the intensive application of N-P-K, and other trace elements. Figure 7.8 also shows that exports of phosphate rock have provided a substantial market for the domestic phosphate mines, and indicates the increasing role of potash imports in the past several years.

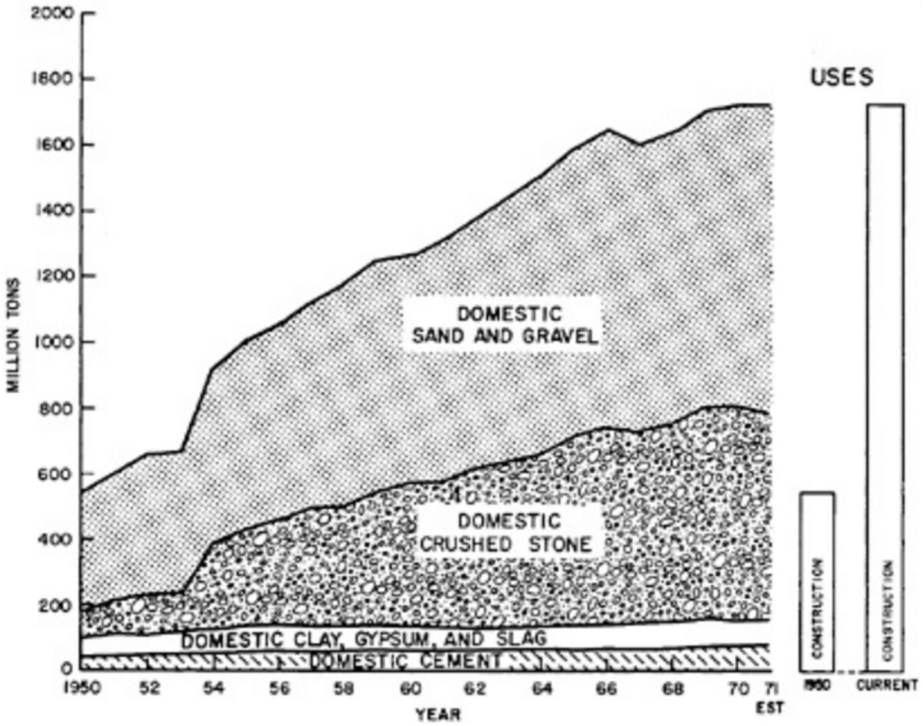
Other Nonmetallic Minerals: Other nonmetallic minerals of importance to the U.S. economy include asbestos, barium, boron, bromine, calcium, corundum, diamonds, diatomite, emery, feldspar, fluorine, garnet, graphite, gypsum, kyanite, lithium, mica, perlite, pumice, quartz, sodium, strontium, sulfur, talc, soapstone, pyrophyllite, and vermiculite.

Asbestos demand is expected to increase domestically at an annual rate of 2.7 to 3.5% over the next few years. The worldwide shortage once predicted for the mid-70's may be alleviated by the regulation of its use because of toxicity. Substitutes for asbestos are being sought for many applications. Currently, about 70% of asbestos consumption is in the cement products and construction field where the fibers are reinforcing agents. Other uses are: floor tile (10%), paper products (7%), transportation products (3%), textiles (2%), paints and caulking (2%), and plastics industries (1%). Nine companies produced all of the asbestos in the U.S. in 1970. Fully integrated companies, which are producer, consumer and end-product retailer, are common in this industry.

Barite demand is forecast to increase domestically at an annual rate of 1%. The U.S. is the world's largest consumer, and while it produces about 20% of the world output, it is still a large importer. The major use for barite is as a weighting agent in oil- and gas-well drilling muds; this accounted for 79% of the 1970 consumption. The manufacture of barium chemicals takes up 10% of barite consumption. Most of the remaining 11% is used as a flux, oxidizer, and decolorizer in producing glass, and as a filler in paint and rubber. Four companies accounted for 69%, and 10 companies for 93% of the 1970 mine output, which was valued at $854,000.

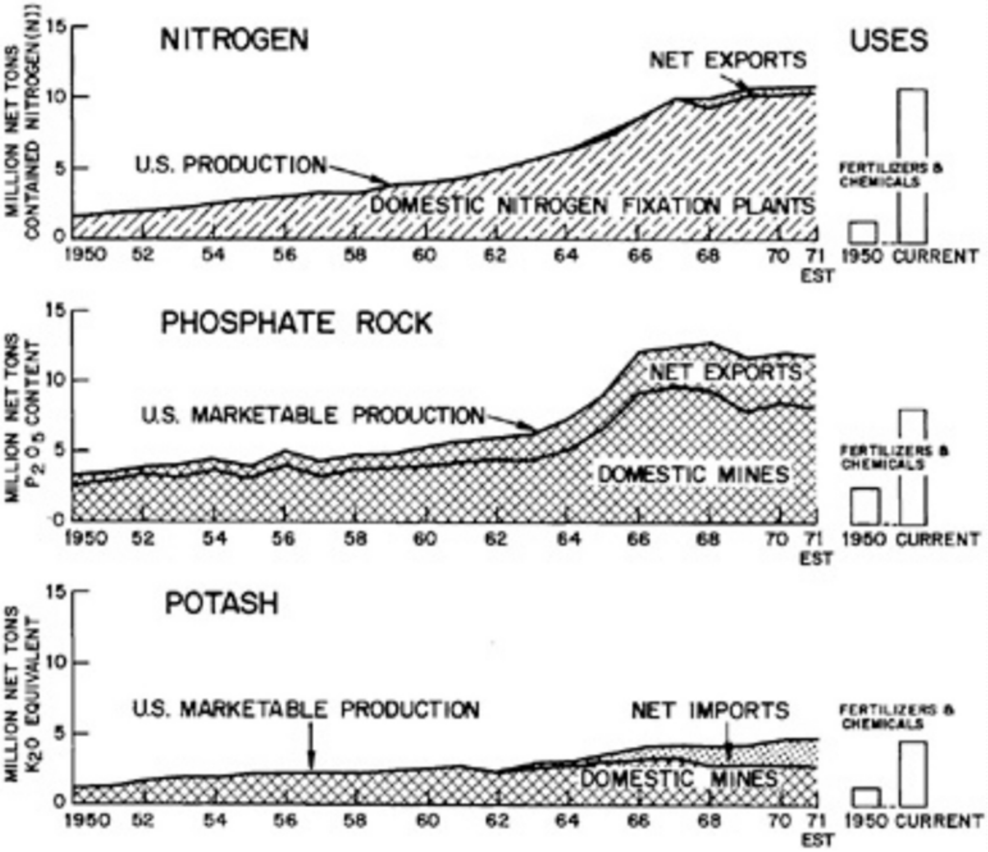
Boron demand is expected to increase at an annual rate of 3 to 4%. For the next twenty years or more, these increased needs are expected to be met

FIGURE 7.7 U.S. SUPPLIES AND USES OF MAJOR NONMETALLIC CONSTRUCTION MATERIALS*



* FIRST ANNUAL REPORT OF THE SECRETARY OF THE INTERIOR, MARCH 1972

FIGURE 7.8 U.S. SUPPLIES AND USES OF MAJOR FERTILIZER INGREDIENTS*



* FIRST ANNUAL REPORT OF THE SECRETARY OF THE INTERIOR, MARCH 1972

largely by expanded domestic production. Important uses of boron compounds are in the manufacture of starch adhesives, ceramics, paints, soaps and detergents, fiberglass, flameproofing, gasoline additives, electrolytic condensers, glass, leather tanning, nonferrous-metal refining, nuclear-reactor control rods, photographic chemicals, and porcelain enamels. Boron compounds are also used in fungus control, herbicides, and agriculture. Glass and glassware accounted for about 42% of total U.S. consumption of boron; vitreous enamel and paints, 10%; soaps, cleansers, and detergents, 16%; fertilizers, 5%; and other uses, 27%.

Clay demand is forecast to increase at an annual rate of 3.5% and will be met by expanded domestic production. Reserves are plentiful and few problems of supply are expected. Imports declined nearly 25% to an all-time low of 64,000 short tons in recent years. Clay uses are many and varied, and sources are widely distributed throughout the country. Principal applications in 1970 were: structural clay products, 40%; hydraulic cement, 21%; and expanded clay, 18%. Other important markets were iron-ore processing, paper mills, and nonferrous metals.

Clay was produced at 1,457 mines in 1970, in all States except Alaska and Rhode Island. Brick plants and cement mills are scattered all over the country. Specialty clays such as ball clay, bentonite, fuller's earth, and kaolin, are produced in localized areas and are shipped throughout the country.

Corundum demand is forecast to decrease domestically at an annual rate of 2%. U.S. requirements, which were met by imports from Southern Rhodesia until trade was stopped because of U.N. sanctions, have been supplied since 1969 from industry and government inventories. A single U.S. company acquired the entire surplus of corundum after the stockpile objective was reduced to zero and this supply was authorized for disposal.

Emery demand is forecast to increase domestically at an annual rate of 3%. However, the number of producers in New York, where the only commercial deposits of emery are found, has decreased to one; and zoning restrictions may close the remaining one. Corundum in its grain or powder form is used as an abrasive for lens grinding, (45%); pressure blasting of fabricated metals (40%); and other uses (15%). Emery is used primarily in the U.S. for nonskid concrete floors (45%), on highways (30%), and other miscellaneous abrasive applications (25%) which include coated abrasives, bonded products, polishing grain, and pressure blasting. One company in Massachusetts is the sole importer, processor, and distributor of corundum abrasives in the U.S. A New York company is the sole emery producer in the U.S.

Industrial diamond demand is forecast to increase domestically at an annual rate of 4 to 5.5%. Much of the increased need can be met by domestic manufactured synthetic diamond (25 mesh or finer). The U.S. has no domestic resources of natural diamond. The principal uses are in dies, grinding wheels, bits, tools, and in lapping and polishing compounds. The principal markets are in the manufacture of transportation equipment, 21%; electrical, 16%; concrete construction, 11%; exploration, 9%; dimension stone, 7%; stone, clay and glass, 4%; and all other uses, 15%.

Diatomite demand is expected to increase domestically at an annual growth rate of about 5%, and can be met by increasing production from existing open-pit operations in the Western States. In 1970, industrial and

and municipal water, food, beverage, and pharmaceutical processing required 58% of the diatomite production; industrial chemicals, 19%; thermal insulation, 4%; and other, 19%. During 1970, nine companies operating 11 plants principally produced and prepared all the domestic diatomite valued at $32.6 million.

Feldspar demand is forecast to increase domestically at an annual rate of 3.4 to 5.8%. These needs can be met by increasing production capacity through more than adequate reserves. (Note: Since a high percentage of feldspar supply is consumed in the manufacture of disposable bottles, legislation regulating their use may significantly alter the market for feldspar.) Feldspar is used in glassmaking to increase workability and chemical stability. Applications are for container glass, 44%; flat glass, 11%; ceramics (principally as a flux), and pottery making, 36%; enameling, 2%; and other uses such as abrasives, scouring soap, fillers, welding-rod coatings, 7%. Three firms accounted for 62%, and 7 firms accounted for 90% of 1970 mine production of the domestic feldspar (650,000 tons total).

Fluorspar demand is forecast to increase domestically at an annual rate of 3.6 to 4.6%, a rate which is faster than the probable domestic supply. In the near future, the importation of fluorspar is expected to continue at current or increasing rates. About 36% of the fluorspar consumed in the U.S. is used in the fluorocarbon industry; 40% in the steel industry; 21% in the aluminum industry; and the remaining 3% in miscellaneous electrometallurgical, chemical, ceramic, and other industries. In 1971, 2 large companies and 13 small companies operated 27 mines in 9 states. Fluorspar ores are concentrated in heavy-media and/or flotation plants. In 1971, U.S. companies produced finished fluorspar having a total value of $17 million.

Garnet demand is forecast to increase domestically at an annual rate of 2.1% for abrasive quality and 4.7% for sandblast quality. The increased needs are expected to be met by expanded domestic production. Uses for garnet are: grinding and polishing flat glass and optical glass, 32%; aircraft, 28%; other transportation, 10%; wood furniture, 10%; plastic products, 6%; semiconductors, 6%; fabricated leather products, 5%; and miscellaneous, 3%. In these applications, garnet competes with other natural and artificial abrasives. One company produces all the abrasive-quality garnet in the U.S. and accounts for all U.S. exports. Three other companies produce sandblast quality.

Graphite demand is forecast to increase domestically at an annual rate of 1 to 2% based on 1969 consumption of 61,000 tons. The increased needs are expected to be largely met, for the short term, by expanded imports. Nationalization of the Ceylonese mines has created uncertainty about future U.S. supplies from there. In 1970, natural graphite was used for foundry facing, 33%; crucibles, 9%; other refractories, 15%; a carbon raiser in steelmaking, 10%; dry lubricants, 10%; pencil leads, 4%; batteries, 3%; truck and bus brake linings, 3%; and other uses, 13%. Two hundred and thirty-five manufacturing plants account for an estimated 65% of graphite. Many small firms consume the rest. Primary metals use 43%; stone, clay, and glass products, 26%; nonpetroleum lubricants, 10%; pencils, 4%; and other uses, 17%.

Kyanite demand is predicted to increase domestically at an average rate of 3.8 to 6.7% annually. This rate could decline substantially if the direct reduction process for steel production becomes commercially feasible. More complete recovery and use of byproducts such as pyrite, silica, and flake mica should be feasible with future advances in technology. The U.S., already the world's largest producer of kyanite and synthetic mullite, could become the largest exporter of these commodities. Nearly 90% of the 1970 consumption of kyanite and mullite was for refractories employed in the production of iron, steel, glass, ceramics, and nonferrous metals. Three firms, each with combined mining and processing facilities, supplied 100% of marketable production in 1971. Synthetic mullite was produced in 1970 by 7 firms.

Mica scrap and flake demand is forecast to increase domestically at an annual rate of about 4.5%. Increasing demand can be met from several domestic resources which are amenable to economic benefication techniques. Although foreign producers will endeavor to increase their future scrap exports to the U.S., domestic production should remain competitive. Good quality scrap mica is delaminated and fabricated into mica paper for the electronic and electrical industries. The remaining scrap and flake is processed into ground mica for various industrial end uses, with a significant quantity of good quality scrap being delaminated for fabrication into reconstituted mica products. In 1970, scrap and flake mica were processed by 20 companies operating 22 grinding plants in 14 states. End uses for ground mica were: mica paper, 4%; gypsum plasterboard cement, 30%; roofing, 25%; paint pigment extender, 22%; molded rubber products, 6%; and other miscellaneous items, 13%. There are approximately 20 flake mica producers in the U.S. The 1970 flake mica production was valued at $2.5 million.

Mica sheet, consisting of block, film, and splittings is expected to decline in demand domestically at an average rate of 8% annually, because of the substitution impact of solid-state electronics and the availability of suitable alternate materials, both mica and nonmica based. Sheet mica is used in the manufacture of vacuum tubes, capacitors, and other electrical and nonelectrical items. Muscovite block and film was consumed by 17 companies in 8 states during 1970. Splittings were fabricated into built-up mica products by 13 companies in 9 states. Six companies accounted for almost four-fifths of total consumption.

Perlite demand is forecast to increase domestically at an annual rate of 3 to 4%. No immediate raw-material source problem is seen. Further growth in consumption is likely to be proportional to the rate of building construction. Expanded perlite is consumed as follows: aggregates (plaster, concrete, and insulating board), 59%; industrial water, food, beverage, and pharmaceutical processing, 23%; thermal insulation, 3%; agriculture, 4%; and other uses, 11%. Crude perlite was produced by 12 companies at 14 mines in 7 states. The value of crude perlite sold and used to make expanded material in 1970 was $4.9 million; the value of expanded perlite sold and used by 89 plants in 33 states was nearly $25 million.

Natural quartz crystal demand is predicted to increase domestically at a maximum annual growth rate of 0.25%. Substitution of synthetic manufactured quartz for natural quartz has lowered U.S. dependence on Brazilian imports. Practically all electronic-grade natural quartz is processed into finished crystals for electronic frequency-control or selection equipment. A very small quantity is used for prisms, wedges, lenses, and other optical purposes. Raw quartz crystal in 1970 was consumed by 26 cutters in 12 states. Quartz crystal is used in the manufacture of oscillator plates, 73%; filter plates, 18%; telephone resonator plates, 8%; and other miscellaneous items, 1%.

Sodium carbonate or soda ash demand is expected to grow at an annual rate of about 4%. In the past, most soda ash has been produced from salt by the solvay process, but an increasing quantity (41% in 1971) is being produced from natural sources of sodium carbonate. New soda ash production facilities are dependent entirely on natural sodium carbonate minerals rather than salt. Some solvay plants have been ordered to close because their effluent could not meet new standards set by environmental protection authorities. Of the total sodium carbonate produced in the U.S., about 50% was consumed in the manufacture of glass, and 40% in the production of other chemicals. The processing of wood pulp into paper required 8%, and the remainder was consumed in soap, detergents, and other uses. Sodium carbonate is derived from natural sources by four companies. Five companies produce sodium carbonate from salt.

Sodium sulfate demand is expected to increase at an annual rate of 4%. In 1971, 46% of domestic output came from natural sources and the remainder was produced by byproducts from salt and sulfur compounds in manufacturing rayon, cellophane, and other commodities. Sodium sulfate is used in the production of kraft paper (74%) and in other miscellaneous products such as glass, ceramic glazes, detergents, stock feeds, dyes, textiles, medicines, and other chemicals. In 1971 natural sodium sulfate was produced by six companies, valued at $12.6 million.

Talc-group minerals demand is forecast to grow at between 2.5 and 4.6% annually. Domestic resources will be more than adequate to meet domestic needs. Talc and soapstone uses in 1970, in order of importance, were: ceramics, 27%; paint, 18%; paper, 6%; roofing, 5%; insecticides, 4%; rubber, 3%; toilet preparations, 2%; textiles, 1%, and other products, 34%. Talc, soapstone, and pyrophyllite are consumed by many firms in all parts of the country. Uses by industry in 1970 were: stone, clay and glass products, 34%; chemicals, 29%; paper, 6%; asphalt, 4%; rubber, 3%; and other uses, 24%. Mine output came from 40 operations and was valued at $7.8 million in 1970. Crude output was processed by about 40 grinders, mostly in the same locations.

Vermiculite demand is predicted to increase domestically at an annual rate of 3.5%. In an expanded form, vermiculite is important commercially as a concrete aggregate and as a thermal insulating material, but faces competition from other low-cost products with similar properties such as perlite and pumice. Improvements to minimize the treatment losses in fine fractions or to provide a market for fine-size vermiculite could enhance the competitive position of vermiculite. Uses for vermiculite are many; it is a loose-fill insulating medium with or without the addition of a binder. Mixed with gypsum plaster, vermiculite forms an acoustical medium for sound absorption; with portland cement, a lightweight concrete results. Gypsum, clay, asbestos, and suitable cements are added to vermiculite to produce a fireproofing medium that can be applied to building structures. Agricultural uses are as soil conditioner, a plant growing medium, and a packing material for nursery stock. Construction utilizes 80% of production; agriculture, 14%; and other uses, 6%. One company accounted for nearly all of 1970 mine output, valued at $6.5 million, from three mining operations. One company predominates in exfoliating and operates 23 large plants in 20 states. In all, 25 companies operate 52 exfoliating plants in 33 states.

Plastics Industry

For the past twenty years, plastics production has been growing at an annual rate of between 10% and 15%. The 1969 production total was about 10 million tons, which is comparable with the nonferrous metals. Moreover, as first pointed out by Houwink[3], the volume of plastics being produced is rapidly approaching that of all metals. Table 7.8 shows cubic feet of plastics, elastomers (rubbers), and fibers for 1968 and 1973 compared with ferrous and nonferrous metals[4].

The production of key plastics by type, based on data by Jenest[5] is shown in Table 7.9 for 1969 and estimated 1974. The "big three" (known commonly as the polyethylene-polystyrene family and PVC) draw heavily on petroleum as a raw material, as shown in Table 7.10. Many additives are employed to modify plastic materials; the scale of their use is shown by the fact that such additives had a 1969 value of $0.8 billion compared to $3.8 billion for the plastic materials themselves[6].

The financial characteristics of the plastics industry have been well summarized by Jenest[5]. Two aspects having a materials orientation are worth noting here. The first is the price-volume relationship. Figure 7.9 is a double logarithmic plot of pounds of different plastic materials sold in 1969 as a function of selling price. The line, as drawn, has a slope of `3, indicating the extreme sensitivity of sales volume to selling price. Certain plastics, notably Nylon 6 and fluorocarbons are sold in greater quantities than would be indicated by their price alone. Secondly, in comparing cost of plastics with metals, the large difference in density often requires that costs be expressed in price per unit volume. For example, a polycarbonate resin selling at about 75c/lb. costs 3.3c/cu. in. Zinc selling for about 18c/lb. costs 4.5c/cu. in. Thus, the polycarbonate is more than competitive with zinc in applications where its properties are adequate, particularly since the polycarbonate is easier to fabricate.

The major types of plastics-fabrication processes in use today[5] are shown in Table 7.11. One significant recent trend in plastics fabrication is that major end-users of plastics parts, such as the appliance and automotive industries, are undertaking the fabrication themselves with large and sophisticated facilities. Another trend is the increasing attention being given to the disposal of post-consumer plastic wastes. Reuse and recycling possibilities are currently receiving greater attention, as well as disposal via energy generation as fuel. Table 7.12 diagrams schematically the waste and recycle aspects of plastics.

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[3] R.Houwink, Modern Plastics, 43, 98 (August 1966) .

[4] R.B.Symour, Ind. Eng. Chem., 61, 28 (1969).

[5] C.H.Jenest, The Plastics Industry, A.D.Little Co., Cambridge, Mass., (October 1970).

[6] The Plastics Industry and Solid Waste Management, Society of the Plastics Industry, Inc., New York, New York (September 1970).

TABLE 7.8 Production of Principal Polymers and Metals in the U.S.

	1968 (Cu. Ft. 10^7	1973 (Cu. Ft. 10^7, Estimate)
Synthetic Polymers	400	710
Plastics	260	500
Elastomers	80	110
Fibers	60	100
Steel and Nonferrous Metals	424	574
Steel	370	500
Aluminum	40	50
Zinc	6	7
Copper	4.5	4.7
Magnesium	2	3
Lead	1.5	1.6

TABLE 7.9 Production of Plastic Materials by Type, 1969–1974

	1969 Production									
Type	Value $ Millions		% of Total Value		Average Price (c/lb., dlvd.)		Billion Lb.		1974 Production Billion Lb.	
Polyethylene		725		19		13		5.5		10.7
Low density	470		12		12		3.9		7.2	
High density	225		7		16		1.6		3.5	
Styrenes		645		17		19		3.4		6.0
Polystyrene[a]	475	13	17	2.8	4.8					
ABS	170	4	28	0.6	1.2					
Polyvinyl Chloride	405	11	14	2.9	4.9					
Phenolic	265	7	22	1.2	1.7					
Polypropylene	250	7	21	1.2	3.0					
Methacrylate	200	6	55	0.4	0.7					
Polyester	195	5	28	0.7	1.4					
Alkyd	180	5	26	0.7	0.8					
Cellulosic	130	3	65	0.20	0.24					
Urea	120	3	20	0.6	0.9					
Polyvinyl Acetate	100	3	25	0.4	0.6					
Epoxy	90	2	50	0.2	0.4					
Polyamide (nylon)	80	2	82	0.1	0.2					
Fluorocarbon	75	2	350	0.02	0.03					
Melamine	60	2	30	0.2	0.3					
All Other[b]	280	7	22	1.3	2.2					
Total	3820	100[c]	20	19.0	34.0					

[a] Includes impact grades.

[b] Includes other vinyls (e.g. saran, polyvinyl butyral, polyvinyl alcohol), acrylates , urethane resins, polycarbonate, silicones, acetal, coumarone-indene, and others; values calculated by subtraction.

[c] Does not add because of rounding.

Sources: U.S. Tariff Commission; Modern Plastics, January and June, 1970; and Arthur D.Little, Inc., estimates.

TABLE 7.10 Percentage Raw Material Make-up of Key Plastics

	Ethylene	Propylene	Benzene	Chlorine	Cellulose	Other
Polyethylene	100	—	—	—	—	—
Polypropylene	—	100	—	—	—	—
Polystyrene	27	—	73	—	—	—
Phenolic	—	—	70	—	—	30[b]
Epoxy	—	37	44	—	—	19[c]
PVC	43	—	—	57	—	—
Cellulose[a]	12	—	—	—	75	—

[a] Cellulose triacetate assumed for calculations. The figure would be 100% for cellophane.

[b] Carbon, oxygen, and hydrogen.

[c] Oxygen.

FIGURE 7.9
PRICE/VOLUME RELATIONSHIP FOR PLASTICS IN 1969 (AFTER JENEST)

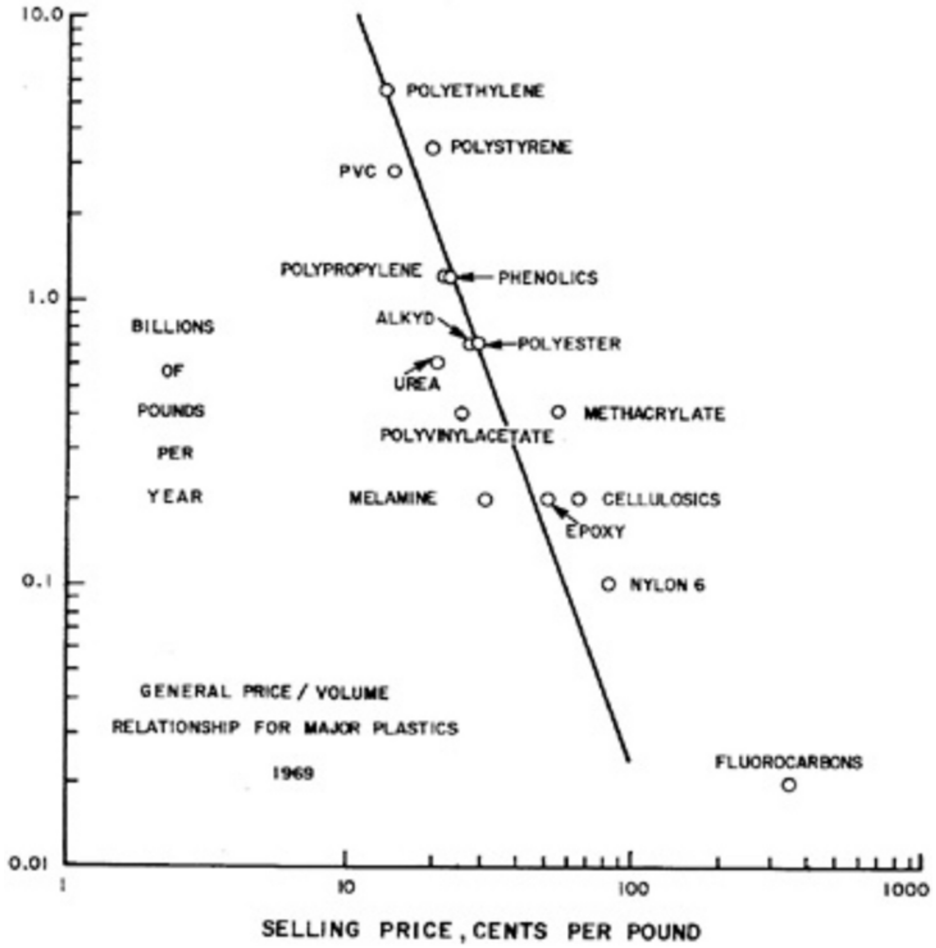
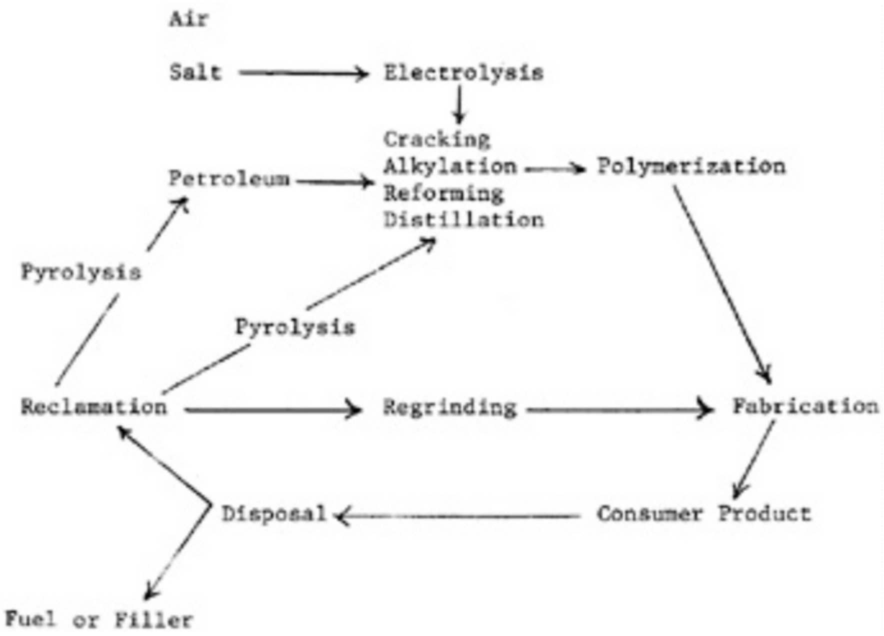


TABLE 7.11 Common Fabrication Methods for Plastics

Casting (curing of liquid components in a mold)
Compression molding
Transfer molding
Injection molding of thermoplastics
Extrusion
Calendering
Blow molding (for hollow shapes such as bottles)
Thermoforming of plastic sheet
with vacuum
with pressure
Rotational molding (for hollow shapes such as gasoline tanks)
Slush molding (with chopped glass fiber—polyester resins)
Injection molding of thermostats
Matched die molding of glass reinforced plastics
Hand lay-up of glass-reinforced plastics followed by heat curing

TABLE 7.12 Materials Cycle for Plastics Industry



Plastics as used for engineering purposes are usefully considered in terms of two major classes—engineering plastics and composition. Engineering plastic materials are specific polymers that have a combination of properties—strength, temperature resistance, solvent resistance, creep resistance, etc. —which permits them to be employed for structural purposes in engineered end-applications. Such materials are nylon, polyacetals, teflon, polycarbonates, polyphenylene oxide, etc. Composites—as the name implies—are mixtures of polymers or of polymers and inorganic materials in physical forms and ratios designed to develop specific properties:

(a) Fiber-reinforced thermoplastics and thermosets: Glass fibers in the form of chopped fiber, continuous roving, and cloth are used to reinforce plastics of both thermoset types: polyester and epoxy, as well as in thermoplastics such as polyethylene, polypropylene, polystyrene, nylon, etc.
(b) Rubber-reinforced (high impact) polymers: The toughness of brittle plastics such as polystyrene, polymethyl-methacrylates, and PVC can be enhanced by blending the plastic with an unvulcanized rubber (elastomer).
(c) Polymer/polymer blends: Polymer/polymer blends are used to improve one or more of such factors as cost, melt processing or physical properties. Since any two polymers are typically incompatible, a rather complex two-phase morphology results. The MSE aspects are similar to those for rubber/plastic blends.
(d) Metal/plastic laminates: A laminate of aluminum sheet and an ethylene-acrylic acid copolymer (for good adhesion) is used as cable sheathing for power and communication cables. Ease of fabrication plus enhanced properties are achieved. A sandwich made of two sheets of metal with an inner core of a plastic having high internal friction is an efficient sound deadener. As with a metal skin on a foamed plastic core, sandwich panels provide a high section modulus, thermal insulation, gas barrier, and light weight.
(e) Plastics in concrete: The brittleness of concrete can be overcome to some extent by incorporating fibers such as nylon and glass, polyethylene particles, or latex.

In its utilization of technical manpower, the plastics industry has traditionally employed the following professionals in the role of materials scientists and engineers:

Organic Chemists
Analytical Chemists
Physical Chemists
Physicists Polymer
Mechanical Engineers
Microscopists
Plastics Engineers
Chemists and Physicists

Sixteen plastic producers list the following distribution of personnel in their R&D operations:

1%	Biochemists
26%	Chemists
7%	Chemical Engineers
1%	Mathematicians
1%	Physicists
22%	Other Professionals
27%	Technicians
15%	Other Support

Finally, in considering long-term ecological aspects of the plastics industry, it is important to recall that the major raw material in plastics has shifted from cellulose to natural gas and petroleum. The trend away from cellulose as a base has been largely an economic one arising from the cost of raw materials and the high capital investment involved in converting natural cellulose to moldable plastics. The average selling price of cellulose plastics (excluding cellophane) is about 65c/lb. compared with an average of 20c/lb. for all plastics and 13c/lb. for polyethylene. It appears unlikely at the present time that, in the absence of legislation based on ecological considerations or a dramatic change in price or availability of petroleum, the plastics industry will expand the use of cellulose derivatives, cellophane film, and chemically-treated wood. Nevertheless, it is worth noting that the greater use of cellulose could have the following effects on ecology in addition to conserving petroleum:

(a) Newsprint and waste cotton fabric might be recycled to become a raw-material base for plastics.
(b) Cellulose-rich plastics might be more biodegradable than hydrocarbon or chlorohydrocarbon polymers.
(c) At the same time, other ecological aspects might be worsened such as greater use of insecticides and fertilizer in the growing of cotton or wood as a raw material for plastics.

Examples of Major Materials-Using Industries

In a very real sense, no industry is independent of materials to construct or produce its products—whether goods or services. Thus, the limited number of industries described in this section have been selected for attention because they illustrate the different ways in which materials enter into the manufacturing process and they also represent key sectors of

U.S. industry. The order in which they are discussed—electronics, electric lamps, containers, automobiles, and construction—corresponds both to an increasing scale of the product involved, and to a shift of emphasis from electrical to mechanical properties in designing materials for the product.

Electronics Industry

Illustration of the Role of Materials Science and Engineering: Even before the invention of the transistor in July 1948, electronics was a substantial industry with an emerging area of manufacture and application of several semiconductors. In fact, a large effort had been exerted on silicon and germanium during the late 1930's and during World War II, principally in support of detector and mixer technology at radar frequencies. Thus, knowledge of the science and technology of both silicon and germanium had become rather advanced both in this country and abroad. However, the 1948 announcement of the first transistor by Bardeen and Brattain at Bell Telephone Laboratories initiated a new era unique in the interplay it engendered between science and technology and between materials and device concepts, a phenomenon that has characterized the industry now for a quarter of a century. This interplay has been complex because of the great number of device requirements and the variations of materials, designs, and processes to be controlled to widely different parameters and to close tolerances. What has resulted is a variety of new electronic materials, new devices, and a wide variety of applications that have had major impact on man's situation in the world and his perception of it.

The current period has been variously called "the computer age," "the space age," and "the age of communications." All of these now-familiar features of the present world have depended crucially on the transistor, and have greatly influenced the character of warfare, international politics, and advances in the automation and control of production processes. The understanding of the solid state that has come as a byproduct of these developments in the electronics industry may turn out to be an even greater contribution. Because of this general importance, it is useful to examine some of the technical developments that have led to this understanding.

In the same year that the invention of the transistor was announced, and in the same Laboratories, Teal and Little began experiments to grow large single crystals of high structural perfection in germanium by a pulling technique to test their idea that grain boundaries and other defects normally present masked the desirable electronic properties. Buehler and Teal also improved the purity by repeated recrystallization methods. These single crystals had, as well as improved uniformity, such strikingly new and different properties in contrast to polycrystalline germanium as lifetimes of minority carriers 20–300 times greater and mobilities 3–4 times greater. Analogous success was attained in early 1951 with preparing single crystals of silicon.

With the development of useful devices, the demands for these high-purity materials increased sharply. Satisfaction of these demands was greatly simplified, in 1951, when Pfann developed a method particularly appropriate for production—the process of zone refining—in which a molten zone is repeatedly passed through an ingot by relative motion between the heat source and the crystal. By the middle 1950's, this identification of the importance of purity was requiring measurement techniques never before considered feasible for routine materials scrutiny, namely, a sensitivity of one part per billion (equivalent to detecting three people in the earth's population).

The first transistor was an experimental triumph in that it was not really clear what processes were actually taking place at the all-important conductor point brought into contact with the semiconductor material. However, during the next year (1949), Shockley analyzed the rectification in p-n junctions and showed the possibility of obtaining transistor action using p-n junctions in bulk material. In response to this development, Sparks devised a unique method for preparing p-n junctions by modifying the Teal-Little crystal-pulling apparatus to allow controlled addition of impurities during crystal growth; the resulting new kind of transistor was first prepared in 1950. These single crystal materials not only provided a revolutionary electronic device, but also gave media sufficiently perfect to test the validity of solid-state theories, and so further their development. The same basic techniques of making multiple junction structures was applied later to silicon, then a more difficult material to work with than germanium, and was the exclusive method for making commercial silicon transistors, beginning in 1954, for several years.

In 1950, an alloying technique was used successfully to prepare single p-n junctions in germanium by Hall and Dunlap of General Electric, and Saby prepared p-n-p transistors in the same manner. Application of the alloying technique to silicon was delayed until an improved silicon purification technique, floating-zone refining, was developed by Theuerer (and independently by Emeis and Keck). Pfann's initial zone-refining method could not be used on silicon because of interaction between the molten silicon and its containing boat. However, other experimenters conceived the idea of setting up a stable molten zone in a vertical rod of material by virtue of surface tension, which meant that zone purification could then be extended to silicon. (Diffusion processes rapidly displaced alloying techniques and alloyed silicon transistors never became as significant as in the earlier application to germanium.)

Engineering demands to make semiconductor devices operate at higher and higher frequencies stimulated work on materials processes that would provide the smaller and smaller geometries that were required. Following original work of Fuller at the Bell Telephone Laboratories and Dunlap at General Electric, the Bell Telephone Laboratories published in early 1956 descriptions of both germanium and silicon transistors made by diffusion techniques. The combination of diffusion technology with the earlier processes, and the device designs made possible by the new approach, produced a wide variety of innovative devices of increasing performance.

During the next year or so, two particular milestones in materials technology were passed which were of special importance in the light of later events: (a) the observation by Frosch that a thermally-grown oxide on silicon impeded the diffusion of certain impurities, coupled with photographic masking against etching, provided a powerful tool for silicon processing; and (b) the studies by Dash of dislocations in silicon resulted in developing methods for growing silicon single crystals with essentially no dislocations.

In June 1960, the Bell Laboratories announced a new method of fabricating transistors using epitaxial single crystals grown from the gas phase with controlled impurity levels. The advantages of this method broke the 12-year-old requirement of having to start with a high-purity crystal and then add impurities in a controlled manner to obtain the characteristics required in the device.

In 1958, Kilby (Texas Instruments) fabricated the first integrated circuit. This concept made possible the implementation of many functions on a single chip of silicon, viz., the elements of a complete circuit, such as resistors, capacitors, transistors, and diodes. Key modifications to the technology already developed for discrete devices included diffusion through the epitaxial layer of an integrated circuit to provide the high resistance of a reversed-bias p-n junction as isolation for adjacent devices and the MOS concept. The field-effect device proposed originally by Shockley, and now called the MOS transistor—for metal-oxide-semiconductor transistor— became possible because of advances in materials surface-treatment techniques; for some applications, the MOS technology, because of its low-power requirements, high-packing densities, fewer processing operations, and other characteristics, turns out to be markedly superior to the conventional bipolar technology. Now, after little more than a decade, the integrated circuit has evolved from Kilby's primitive phaseshift oscillator to the high-production manufacturing of circuits with over 10,000 components apiece.

The preceding discussion provides an illustrative example of some of the significant advances made in electronic materials. It is confined to semiconductor work with the two significant elemental materials, germanium and silicon; and dwells principally on the beginnings through the 1960's with only sketchy reference to the recent years. Nevertheless, the outline does demonstrate the tremendous degree to which the materials technologist has achieved control of electronic materials: for example, the extremes of purity; the control over doping at very low levels; the variety of techniques for creating junction structures by introducing impurities at exactly the right positions in the lattice and with very close tolerances on their positions and concentration profiles; the intricate combinations of single-crystal regions in device structures; crystals of high structural perfection; crystal-growth techniques.

An additional, but especially important, point is the cross-fertilization effect for research on other classes of materials. For instance, the extended study of semiconductor crystals has increased understanding of the mechanical behavior of structural materials; dislocations were first seen in semiconductor materials, and much of our direct knowledge of defects in solids was obtained initially from studying these materials. The creation of dislocation-free crystals was of great significance for the scientist and engineer working with nonelectronic materials.

At the time of the invention of the transistor, solid-state physics was a minor part of physics, but now it is the largest single subfield of physics. The present sophisticated understanding of the electronic structure of solids grew from the semiconductor work, first on carrier behavior and then followed by the study of band structure.

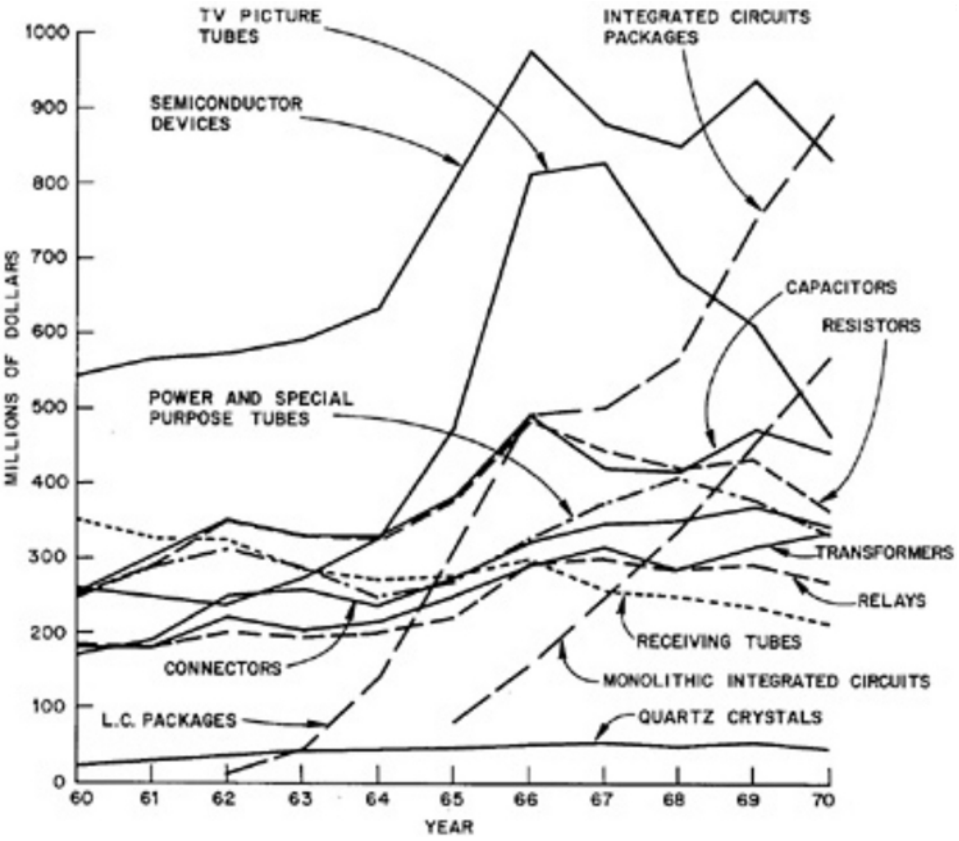
An unique aspect of the advances in electronics materials described above is the pace. As indicated by the sequence of dates, achievement after achievement crowded one upon the other, somewhat reminiscent of the urgency of wartime development of technology. During the decade when the principal production consisted of discrete devices, process gave way to process in such quick succession that manufacturers hesitated to invest in technically possible mass-production equipment because it might become obsolete in literally a few months. Although the normal research communication media of journal publications and seminars continued to be used, the visit and the telephone seemed to have become the mode of exchange among scientists, metallurgists, engineers, and the many varieties of production people. In this mode, it is often difficult to determine in which of the conventional disciplines a given individual is acting. An additional feature was that the sequence of invention often was reversed from the older concept of first conceiving the device and then developing the material which makes it possible; in many instances, it was research on semiconductor materials that laid the basis for a new device design.

Some Characteristics of the Electronics Industry: Figure 7.10 shows the values of shipments of electronic components by U.S. manufacturers for the years 1960–1970. These particular components can be regarded as the major ones in the industry. The various curves are mutually exclusive except that the “monolithic integrated circuits” are also included in the data for the more general “integrated circuit packages.” The most important components on the basis of 1970 values are seen to be the “integrated circuit packages” and “semiconductor devices;” each being close to $900 million. Next, fairly tightly grouped, are: TV picture tubes, $464 million; capacitors, $440 million; resistors, $365 million; connectors, $346 million; power and special purpose tubes, $337 million; transformers (and reactors), $335 million; relays (for electronic applications), $271 million; and receiving tubes, $212 million. Finally, having declined in relative importance over the 1960’s, are quartz crystals at $45 million.

The shapes of the curves shown in Figure 7.10 are especially significant as indicators of the stage of maturity of a given device. Thus, the topmost curve for most of the decade, semiconductor devices, displays the characteristics of a “mature” industry—the leveling-off being associated with its partial replacement by integrated-circuit packages. Its principal predecessor, receiving tubes, is past maturity and is now steadily declining. It is interesting to note that the power and special purpose tubes, which are not as easily replaced by semiconductor devices or integrated circuits, still maintain an upward trend. For the TV picture-tube curve, the unusual shape arises largely from the superposition of two curves—black and white TV picture tubes and color TV picture tubes. In 1970, total shipments were about 9 million tubes (3 million black and white and 7 million color), and the ratio in per-tube value had declined to about 4.5.

Six classes of components appear to be holding essentially steady growth. These are capacitors, resistors, power and special purpose tubes, connectors, transformers (and reactors), and relays. All had comfortable growth experience with no prominent peaks, starting the decade in the range from $169

FIGURE 7.10 VALUE OF SHIPMENTS OF SELECTED ELECTRONIC COMPONENTS (BUREAU OF DOMESTIC COMMERCE)



million to $255 million and ending in the range from $271 million to $440 million.

The most spectacular curve in Figure 7.10 is that for integrated circuit packages, which is roughly paralleled by its subclass, monolithic integrated circuits. Starting at $14 million in 1962, integrated circuit packages achieved a rapid climb to $888 million in 1970, an average increase per year of almost 68 percent for eight years. Monolithic integrated circuits started at $85 million in 1965 (the first year for which statistics are available) and reached $576 million in 1970, an average increase per year of almost 47 percent in five years. Over this same period of five years, the whole integrated circuit class averaged 23 percent growth per year.

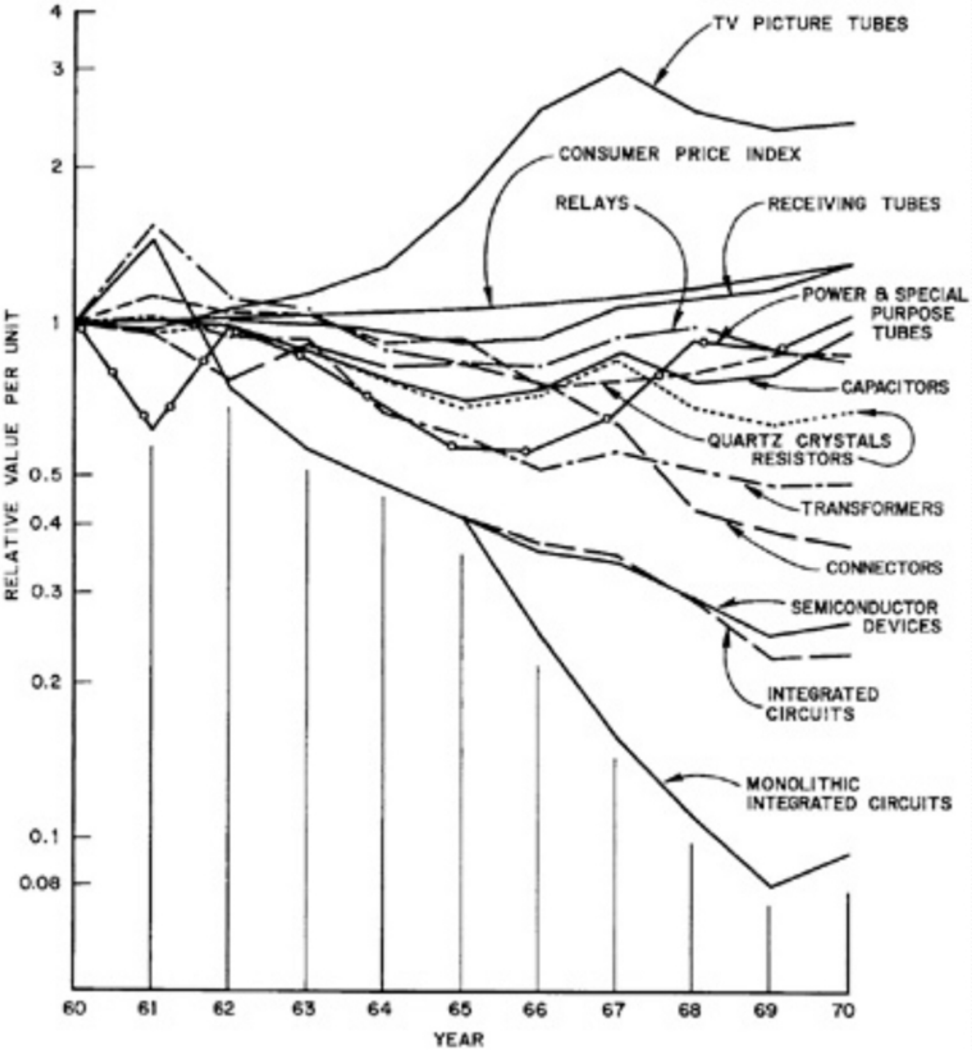
Whereas value of shipments is a useful industry measure of a components sector performance, from the users' point-of-view the better measure is price for comparable quality and quantity. Such a measure is indicated in Figure 7.11, where all unit values for the components are normalized to unity in 1960. For reference, the analogous consumer prize index is also plotted to provide a measure of inflation over the period. A significant general characteristic is the stiffening of per-unit values from 1969 to 1970, when curves tend to change slope toward a positive direction. As in the previous figure, the most distinctive behavior is exhibited by integrated circuits; assuming that this sector branches off from the parent semiconductor devices in 1965, the equivalent per-unit value declined by 1970 to less than one-tenth that of 1960. Even the semiconductor devices, which have a history of continuous decline in unit-value over the whole decade, still have a per-unit value in 1970 of 26% compared with the value in 1960.

Processing of Semiconductor Materials: The most commonly used semiconductor material in the electronics industry is silicon. Next to oxygen as the most abundant element, silicon makes up about one-fourth of the crust of the earth. Not found in elemental form, it occurs chiefly as the oxide, silica (SiO_2), and as various silicates in such familiar forms as sand, quartz, rock crystal, amethyst, agate, flint, jasper, opal, etc. Almost without exception, the type required by the electronics industry is monocrystalline, high-purity silicon; this is prepared by reducing silica with carbon to produce metallurgical grade silicon (98–99% purity), as the usual "raw material" for the electronics industry.

The characteristics of semiconductor materials that make them useful in electronic devices are profoundly influenced by impurities. Controlled addition of desired impurities (dopants) in the range from 0.001 to 100 parts per million (in silicon) to the high-purity host material causes it to become either a p-type (positive holes being the majority carrier) or n-type (negative electrons being the majority carrier) conductor. In "bipolar" transistors, certain sensors, and diodes, the electrical behavior of the junction between p-type and n-type materials accounts for the basic function of the particular device. Accordingly, semiconductor-device technology is focused principally on the controlled doping of materials and the formation of junctions between materials of different impurity concentrations while maintaining a continuous single-crystal structure, without appreciable defects, from one side to the other of each junction.

For the preparation of multiple junctions, successive dopants are added

FIGURE 7.11 PER UNIT VALUE OF SELECTED ELECTRONIC COMPONENTS



by diffusion; the silicon slice is held at a temperature in the range from 900 to 1300° C (depending on the dopant and the desired results), and a carrier-gas bearing the impurity is passed over the slice. Diffusion depth and concentration are controlled by the time and temperature of exposure as well as by the chemistry of the dopant gas.

To provide insulation between layers or to install a mask against a succeeding diffusion, silicon dioxide is grown on the silicon surface by heating the silicon and exposing it to oxygen or steam. Selective diffusion or placement of a contact is done by cutting a window through the silicon dioxide layer to get at the semiconductor surface. (A similar process is used to etch selectively the metallized layers into the desired configurations of electrical conductors.) To make ohmic (nonrectifying) electrical contacts on the semiconductor material or electrical conductors, aluminum or gold is vacuum-evaporated onto all exposed surfaces.

By a succession of steps like those described above, hundreds of microscopic, intricate circuits made up of transistors, diodes, resistors, and capacitors are created on a single 2-inch slice of single-crystal silicon. The representative processes discussed show how the steps of material processing, device design, circuit design, and system design have been telescoped and blended so that one activity often cannot be distinguished from another.

In contrast to these developments in integrated circuitry, which are focused on the task of packing more and more components (of the order of 10,000) into tiny chips of silicon, progress in another branch of silicon technology has led to large discrete devices capable of controlling power in the 10 to 100Kw range. The basic element used to perform this function is the thyristor, the semiconductor analog of the gas-discharge thyratron. Thyristors range in size from those used in light dimmers and speed controls for home appliances up to large industrial devices capable of controlling load currents of hundreds of amperes at a thousand volts or more. They are now being used to rectify and invert power for DC transmission lines at the 100Mw level.

The applications for individual semiconductor devices and integrated circuits are increasingly requiring improvement in the economics of materials usage as well as in performance and reliability. To reduce overall process costs in integrated circuits, the trend is toward 3-inch or larger diameter starting crystals. Such large diameters are generally achieved by pulling the crystals from quartz crucibles—a technique that serves the larger part of the semiconductor market. For the thyristor, in order to avoid the traces of oxygen found in crystals pulled from quartz, long-lifetime float-zone material is used almost exclusively. Since the working current that can be controlled by a single thyristor is limited by the diameter of the starting crystals presently available, there is strong incentive for obtaining material of the highest quality in purity and homogeneity together with still larger diameters. Such enhancement in quality may also lead to improved electrical performance in terms of higher voltage ratings.

Another illustration of the critical dependence of device performance upon material quality is afforded by the semiconductor detectors used for measuring the energy spectra of nuclear particles. For example, gamma-detectors consist of germanium p-n junctions, reverse biased, and operated at liquid nitrogen temperature; the absorption of a gamma ray produces a pulse of current whose amplitude gives an accurate measure of the energy of the gamma ray.

Until recently, a process extremely difficult to control reliably—the lithium-drift process—had to be invoked as a means of compensating residual impurities in order to obtain the very thick depletion regions that are required for high sensitivity in this device. The new availability of germanium crystals of increased purity (large, highly perfect crystals, containing less than 1 part in 10^{12} of residual electrically active impurities) now make it possible to fabricate the equivalent detector structures without the attendant pitfalls that have beset the lithium-drift process. The development of material of this unprecedented level of purity depended on new approaches to the detection and elimination of trace impurities, along with significant advances in the techniques of measurement and characterization.

Figure 7.10 shows a 1970 value of $832 million for semiconductor devices. Of this total, $172 million represent "special and light-sensitive semiconductor devices," many of which are made from compound semiconductors— mostly from the chemical groups III and V. Compounds of the II–VI and IV–VI types are also receiving some attention. The devices in this area include infrared detectors, electroluminescent devices, electron-emission devices, thermoelectric devices, microwave devices, high-power laser windows, and solar cells. The following paragraphs outline some of the key materials features involved in such solid-state products.

Infrared detectors, developed initially for military use, are now finding more general application. The ability of these devices to delineate heat sources makes them useful in such techniques as specialized geographical mapping from aircraft and in clinical detection of human abnormalities. The relevant electronic materials of current importance are indium arsenide, indium antimonide, mercury-cadmium telluride, lead-tin telluride, doped germanium, and doped silicon. The specific choice for a given application depends principally upon the desired wavelength range of sensitivity, which in turn depends upon the characteristics of the radiation emitted from what is to be "seen."

Electroluminescent devices utilize the phenomenon that when current is passed in a forward direction across a p-n junction in certain III–V compounds, radiation of optical wavelength (sometimes in the infrared) is emitted. Optically, this can be handled by collecting the light incoherently, or a laser beam can be generated along the junction. The present light-emitting diodes (LED's) that exploit such effects are made from gallium arsenide, gallium phosphide, alloys of gallium arsenide-phosphide or of gallium-aluminum phosphide. With the gallium arsenide, which is the LED material, infrared emissions can be produced at room temperatures with an efficiency ranging from 10 to 30 percent. The LED's of brightest visibility are in the red-yellow-green range. In the case of room-temperature laser diodes (which are now made of gallium arsenide and aluminum-gallium arsenide alloy), the critical processing technique is to form a heterojunction to guide the growing optical wave that constitutes the laser beam. In the optimum process, instead of changing just the nature of the dopant (which is measured in only parts per million) from one side to the other of the junction, alloys of varying composition are deposited exitaxially to form the heterojunction directly.

Electron-emission devices are long familiar in that, for several decades, many different electronic devices have depended on emission of electrons from solid surfaces into vacuum; the most familiar example is the vacuum tube with its heated cathode. Two newer ways of causing emission at the cathode (photoemission) and the impact of electrons liberated in this process on further electrodes (dynodes) causes secondary emission. However, the fundamental problem in all three kinds of emission from surfaces is the same: more emission is desired with the same or less energy. Progress in overcoming this problem has been achieved through semiconductor technology, where its “principle of effective negative electron affinity” (NEA) has already improved the performance of photomultiplier tubes an order of magnitude over what was possible with the older photocathodes. As a result, photomultiplier sensitivity is reaching into the infrared wavelengths of low photon energy.

Thermoelectric generators were originally attractive because of the possibility of high conversion efficiencies in devices which have no moving parts, operate silently, and require little maintenance. However, in practice, efficiencies have reached only some 10%, and 5 to 7% is more common. Nevertheless, in spite of high cost and low efficiency, numerous important applications have been found where remote, unattended power sources are desirable. Good examples are telephone repeaters, unmanned lighthouses and navigation buoys, space satellites, and scientific instruments on the moon.

In the case of microwave devices, relatively conventional semiconductor units already serve in a number of applications—compact power sources, amplifiers, mixers, and demodulators. More recently, the special property of gallium arsenide, negative differential mobility, has provided a new dimension for the design of microwave devices. Thus, while silicon transistors and trapped-plasma-avalanche-transit-time (TRAPPAT) oscillators can operate effectively up to about 4 GHz, gallium arsenide devices take over—on the basis of noise, power, bandwidth, and efficiency—up to approximately 30 GHz (millimeter waves). These devices operate as transferred electron oscillators (TEO) in either the domain (Gunn effect) or limited-space-charge accumulation (LSA) modes and as Schottky barrier (SB) impact-ionization-avalanche-transit-time (IMPATT) oscillators. Most gallium arsenide microwave devices require an epitaxial layer 0.5 to 20 microns thick on the arsenide substrate, which itself must have a low density of defects in order to avoid their propagation into the thin layer. Gallium arsenide mixer diodes, while competing with silicon diodes in the 2 to 10 GHz range, are used exclusively in the millimeter range because of superior noise figure and conversion-loss characteristics. Gallium arsenide variable capacitance (varactor) diodes are employed currently as low-noise, radio-frequency amplifiers and as nonlinear elements in frequency-multiplication channels of digital communication systems; an anticipated new application is for UHF television tuning.

Windows for high-power lasers is an increasingly important application for semiconductor compounds. As greater and greater optical powers are designed into lasers, sometimes many megawatts per square centimeter, interactions between the beam and the material through which it is transmitted occur and failure of the material results. The most common failure mode is thermal fracturing caused by stresses due to thermal gradients, although sometimes the heating causes failure by melting and flowing. Gallium arsenide, unlike most materials used for windows, resists such failure modes and is stable until dissociation occurs at extreme loading. Currently, the wavelength ranges in the infrared of most importance are 2 to 6 microns (which is receiving most of the attention) and the region around 10.6 microns of the several alkali halides, II–VI and III–V compound semiconductors, germanium, and three commercially available infrared materials explored as window materials; monocrystalline gallium arsenide with resistivities above 10^4 ohm-cm looks especially promising.

Solar-cell conversion is almost unique among power-generation processes in not causing thermal, gaseous, or particle pollution; consequently, interest in terrestrial application is strong. The major barrier is the high cost of making solar cells; this cost would have to be reduced to about a hundredth or even a thousandth of the present level to make such devices economical. Unfortunately, progress has been slow and over the last ten years efficiencies of silicon cells have improved only by about 20%. A possible hope for terrestrial applications is the II–VI semiconductor, cadmium sulfide, in that it can be used in polycrystalline form for solar cells and, because single-crystal technology is not required, may overcome the cost problem. The photovoltaic mechanism in this material is still not well understood, and cells made by a wide variety of techniques all seem to end up with the same properties and operational characteristics. For space application, the III–V semiconductor, gallium arsenide, which has been explored as a solar cell material for 15 years, compares favorably with silicon in the two desirable space characteristics of radiation resistance and high-temperature operation (to 250° C), but such devices would cost at least ten times as much as current silicon cells.

<u>Challenges in the Application of Solid-State Materials</u>: Despite the revolutionary advances that have been made in electronics solid-state materials for use by industry, a number of major problems remain to be resolved. This section identifies the most critical of these items and indicates the current state of progress.

First, there is an urgent need for a better awareness and scientific understanding of the interplay between materials, processing, and device technology. From the point-of-view of materials, this understanding rests heavily on characterization. It is no longer sufficient to effectively characterize only the starting materials, but also to apply the techniques necessary to measure all the useful attributes of the subsequent device materials throughout the whole manufacturing sequence to the finished product. Although the ultimate reason for applying materials in the electronics industry is to insure effective performance of a device or system in service, too often the thinking that starts with materials research and ends with the operation of the complete system is too compartmentalized. The materials specialist tries to meet the specifications set by the device expert, who in turn aims to satisfy the circuit designer, who is trying to fit his designs into the subsystem, etc. As a result, there are too many “catalog” items used in each sequence rather than an overall optimization. Since the overall goal is, in fact, maximization of performance for minimum total cost (that is, the ratio Performance/Annualized Cost of Manufacture, Installation, Operation, and Maintenance), it would appear that increasing this ratio requires some concentration on the final performance from the very beginning. One procedure that would help make this happen is field-failure reporting and analysis—both during initial development of the device or system and also during commercial operation so as to continue the improvement. As an example, hybrid systems, the interconnections of similar and different integrated materials subsystems, are currently expensive to fabricate. If batch processing from the raw materials to final assembly were planned as early as the applied research on a given hybrid system and applied during development rather than deferred to pilot production, cost reduction could be expected from lower initial costs through greater yields, and also from lower annual service cost due to increased reliability through better process control.

Some broadly applicable materials areas which require improvements are the following. Research on the effect of so-called nondoping impurities such as oxygen and carbon is needed to clear up many anomalies observed during processing. Thus not enough is known about the theoretical and practical limits of parameters like minority and majority carrier lifetimes as a function of impurity content. Likewise, continued research effort is required on the potentially useful class of amorphous semiconductor materials; without basic understanding of their behavior, device work is likely to be premature and wasteful. With respect to measurements, more effective methods are needed to determine the chemical purity and electrical characteristics of silicon at all stages of manufacture from raw chemical input through polycrystalline deposition, single crystal growth, and epitaxial deposition. In-process control measurements incorporating nondestructive testing and “adjust” techniques (like electron-beam or laser-beam testing) could increase yields and produce better devices. In addition, since the precise measurement of epitaxial-layer thickness and resistivity becomes progressively more difficult as the layers become thinner with advancing device technology, the development of improved rapid, nondestructive methods for characterizing such thin layers would be of substantial value in almost all device developments. In connection with processing, the preparation of silicon slices by sawing, lapping, and polishing wastes more than half the starting material, and more economic slice-producing methods are needed both for existing and newer applications. For example, to reduce parasitic capacitance (thus increasing speed) in MOS and bipolar circuitry, an economic supply of very thin silicon on insulating supports is essential. In the fabrication of materials and devices, much more use could be made of particulate radiative methods for planned introduction of defects—as by ion implantation, sputtering, or electron-gun evaporation. In particular, ion implantation can lead to device characteristics that cannot be achieved with more traditional processes. For the preparation of conducting films, present methods of applying metals in device fabrication, assembly, and packaging are far from satisfactory in that the high-temperature processing steps tend to be destructive to present metal systems. The phenomenon of ohmic contact remains little understood. Passivation films in the form of improved dielectrics that can be deposited at low temperatures are needed and better film-characterization techniques have to be found for silicon nitride, silicon dioxide, and aluminum oxide. The availability of a truly hermetic low-temperature passivation layer would markedly improve the reliability of semiconductor devices and reduce packaging costs.

As device geometries continue to shrink in size, new processing problems appear. Consequently, imaging technology to transfer mask and other configurations of the order of one micron and below will have to be mastered within a few years. Again, dielectric-silicon interfaces become more critical because impurity and structural defects at these boundaries can dominate the electrical behavior of the device. Finally, in this listing of processing problems, it is important to point out that packaging and testing before and after packaging account for a large part of total device cost. In this light, research and engineering expended on these tasks is likely to have considerable benefit on both cost and reliability.

Turning now to specific devices, the following notes delineate research problems or development areas that require particular attention. In electron-emission devices, laser applications would benefit by increasing photocathode response at 1.06 micrometers (for neodynium-doped yttrium aluminum garnet) and by extending the long wavelength response to 1.6 micrometers (for eye-safe erbium-doped yttrium aluminum garnet). Applied research on III–V alloy systems is a promising approach for the first objective; exploratory materials research is required for the second. To attain the transmission mode required for imaging applications of electron-emission devices, thin crystal layers will have to be grown on a substrate transparent to the incident radiation. Moreover, a heterojunction technology having a graded alloy region between the substrate and photocathode material has to be developed. In spite of a trend from vacuum electronics to the solid state, a real need persists for a practical cathode capable of operating near room temperature and at high current densities. To meet such a need would appear to require appropriate research on III–V semiconductors and their alloys.

In microwave-device research, improved reliability and higher yield of gallium arsenide devices are important goals. Related to these is an obvious role for better correlation between device performance and materials properties.

In thermoelectric research, the major problems common to all telluride alloys are related to their poor mechanical properties and chemical instabilities. Particular difficulty is encountered in fabricating contacts with these alloys at the hot junctions of power-generating thermocouples.

For high-power laser windows, the solution of the failure problem seems to lie in gallium arsenide developments, although this is sufficiently uncertain of success that it should be backed up by exploratory research on other materials.

For solar cells, improvements in resistivity and lifetime of the starting silicon are essential. Again, developments of new materials applications may also point the way to significant terrestrial application of these devices.

Infrared detectors, in contrast to the above two kinds of devices, operate so close to ideal performance when made correctly that there is no real need for exploratory research on new materials. Instead, effort is required in the processing to maintain stoichiometry, structural perfection, purity, and chemical homogeneity.

Electroluminescent devices, somewhat like infrared detectors, are being made out of satisfactory material, provided that red and orange-yellow-green are acceptable colors; but chemical purity, crystal quality, and limitations of seed substrates need considerably better control.

In magnetic materials, ferrite and ferromagnet properties depend on the nature of inhomogeneity and aggregation, which are inadequately characterized with present techniques. Single-crystal ferrites particularly require better characterization, and fabrication methods for new high-energy-product ferro-magnetic materials are inadequate.

In the new magnet-bubble technology, both the fabrication and the characterization of the propagating material are still difficult, and methods of detection of the magnetic bubbles need improvement.

In composite structures, the chief problem is the characterization and understanding of defect and impurity interactions in insulating films and at insulator-metal, insulator-semiconductor, and insulator-insulator interfaces. Particular examples are the influence of hydrogen on silicon dioxide, doping at insulator-semiconductor interfaces, the effect of the metal-insulator interface on metal-insulator-semiconductor device properties, surface charge buildup on insulating layers, lack of integrity of metal and insulating films, measurement of film and interface properties, and metal systems for contacting semiconductors. Other problems are the development of nonsilicon systems for special purposes and the development of ambient gas and pollutant detectors.

Among the needs in inorganic dielectric materials are optical materials for information storage and display, glasses and crystals suitable for communication networks at optical frequencies, improved dielectric materials at microwave frequencies, better dimensional stability in materials for filters and resonant structures at optical and microwave frequencies, adequate substrates for growth of single-crystal films, and higher dielectric-constant and dielectric-strength materials for capacitors.

Finally, in organic dielectric materials, problems lie in uniformity, purity, reduction of voids, compatibility with associated materials, insufficient thermal conductivity, the difficulty of making thin sheets, films, and coatings, microcharacterization, the number of different materials in use, and stability. Stability must be maintained relative to temperature and mechanical changes. In certain applications, the organic material must also display stability against moisture and oxygen transmission.

Electric Lamp Industry

The devices by which electrical energy is converted into light originated with the carbon-arc lamp. The more convenient and more broadly applicable method of illumination created by Edison's invention of the carbon filament or incandescent lamp in the 19th century rapidly transformed domestic and public lighting away from the earlier gas lamps. The range of contemporary lamp types includes discharge, fluorescent and photoflash lamps. However, as shown by Table 7.13, the incandescent lamp (using a tungsten filament) continues to be the dominant device produced by the lamp industry.

In all of these lamp types, the availability of suitable materials has been critical to the device function. The actual materials involved are few in number and relatively modest in the amounts consumed by the industry (see Table 7.14). Nevertheless, each performs a unique function, and the

TABLE 7.13 Lamp Production for U.S. Market, 1969

Type	Volume (millions of units)	Value ($ millions)
Incandescent Lamps	1480	264
Automotive Lamps	602	44
Fluorescent Lamps	254	165
High-Intensity Discharge Lamps	6	37
Photoflash Lamps	1452	105

The overall growth rate of the lamp industry is approximately 4% per year.
The total employment is 40,000`50,000.

TABLE 7.14 Materials Consumption Estimate for U.S. Lamp Industry, 1969

Material	Volume (thousand lbs.)	Value ($ millions)
Tungsten	308	15
Glass—soft and hard	550	11
Fused Silica	1.8	6
Phosphors	10	20

successful evolution of the industry has been controlled in large part by the developments in materials processing and performance. The following paragraphs illustrate some of the material characteristics for each of the major types.

It is obvious from the high-technology content of electric lamps, and particularly from the great importance of the relevant materials, that materials scientists and engineers are key people in this field. There are no specific statistical figures available, but an approximate estimate is that there are 300–500 professionally trained people engaged in work closely related to materials technology in the U.S. lamp-producing industry.

In the original carbon-filament lamp, the most critical and obvious materials problem was the provision of the filament itself. In practice, many materials problems had to be solved before the Edison lamp became reliable and reasonable in cost. Thus, a suitably transparent glass had to be fabricated to the desired envelope shape and thickness, by a processing technique suited to high-speed production. Suitable seals had to be developed so that the electric power could be led to the filament inside the evacuated envelope. The transition to the modern incandescent lamp using a tungsten filament required the development of a material and a powder-metallurgy process that would provide a metal with sufficient ductility so it could be drawn into the fine wire needed for filaments and would retain its integrity over a long operational life. The advantage of the tungsten filaments was in their ability to operate at higher temperatures compared to carbon filaments, resulting in more light in the visible wavelength range per watt-hour of energy expended.

Despite the substantial technological advance with this type of filament, a major limitation on the life of tungsten lamps has been the progressive thinning and eventual failure of the filament due to evaporation of the tungsten at the elevated operating temperature. To overcome this problem, a small amount of a halogen is included inside the lamp envelope. In the so-called iodide or halide cycle, when tungsten is deposited on the lamp envelope, it subsequently chemically combines with the halogen to form a volatile tungsten halide. These halides, however, are unstable at the higher temperature of the lamp filament. When a molecule of the halide comes into contact with the lamp filament, it is decomposed, redepositing the tungsten on the lamp filament and regenerating free halogen to transport more tungsten from the envelope to the filament. In this way, the envelope wall is kept clean, the filament can be operated again at higher temperatures, and the light output per watt is increased. Today, tungsten-filament incandescent lamps are in extensive use—in particular, for household illumination and for headlamps and other lamps in automobiles. It is interesting to note that the use of lamps in automobiles has increased from the initial two headlamps and a tail-light to more than 20 lamps per automobile.

In discharge lamps, light is produced by electronic transitions in the plasma of an electric arc. A typical high-pressure mercury lamp consists of a 400-watt arc inside a fused-quartz arc tube, which in turn is encased in an outer glass envelope. A small amount of fluorescent material (phosphors) is placed on the inside of this envelope in order to convert part of the 365 nm ultraviolet mercury line to visible light. Otherwise, the useful light from a mercury vapor lamp is confined to the four longer wavelengths: 405, 436, 546, and 578 nm.

It is the higher bulb temperature of these discharge lamps that requires the use of vitreous silica (or “fused quartz”), which is substantially pure SiO_2, rather than conventional glasses. Nevertheless the operating efficiency of these lamps has been restricted by the “materials problem” arising from the corrosion resistance and operating temperature limitations of the fused quartz. In about 1955, the use of an improved envelope material became possible in that research led to new understanding of the factors controlling sintering and then to the development of processes for making aluminum oxide (corundum) with theoretical density. The essential discovery was of additives that would reduce grain-boundary mobility, in order to avoid the normal exaggerated grain growth. (This discontinuous grain growth results in a porous ceramic which appears white because incident light is scattered.) A pore-free ceramic transmits well over 90% of the incident light. Furthermore, corundum has a much higher melting point than does silica glass, and is much more resistant to attack by alkali metal vapors. Hence, the availability of pore-free alumina allowed for improved lamps as well as other kinds of discharge than those based on mercury. With a translucent alumina envelope, a sodium vapor-discharge lamp can be made to operate without envelope deterioration at high temperatures and with high sodium pressures. As a result, more atomic transitions in the plasma are excited, and the lamp produces a continuous spectrum of nearly white light (it is slightly green-deficient). This advance in materials provided for the first lamp with a continuous spectrum operating at over 100 lumens per watt.

The fluorescent lamp is essentially a mercury discharge lamp operated at a very low mercury pressure (10^{-5} atmospheres) so that about 60% of the radiation is at 253.7 nm wavelength. This ultraviolet radiation excites fluorescence in phosphors which are coated on the inner surface of the tubular lamp envelope. The basic phosphor in white fluorescent lamps is calcium halophosphate and various additions are made to modify or control the color of the lamp.

Photoflash lamps represent the only important illumination device involving a chemical reaction to heat matter to incandescence. The initial photoflash lamps, developed in Germany, consisted of aluminum foil in an oxygen-filled glass envelope, which could be ignited by an electrically fired primer, so that the foil burned to Al_2O_3 in about 20–30 milliseconds. Subsequent developments have substituted wire for foil, shredded zirconium and, most recently, shredded hafnium metal for aluminum. As a result, the light output per unit volume has increased several fold. Meanwhile, the use of these lamps by amateur photographers has increased to the point that more lamps are produced for flash purposes than any other single application.

Container Industry

The container industry is the largest segment of the packaging industry; it is defined, for the purposes of this report, as that part of the packaging industry involved in the manufacture of rigid packaging such as cans, bottles, boxes, and tubes. The balance of the packaging industry can be described generally as involved in the manufacture of flexible packaging, such as pouches, wraps, strapping, bags, etc. Figure 7.12 illustrates the normal flow of packaging, including containers, from manufacture to disposal or reuse. In the following, each of the principal classes of containers—glass, plastic, metal, and paperboard—are reviewed from the point-of-view of materials needs, availability, and recycling characteristics.

Glass Containers: The continued growth of glass-container shipments from 1900 to 1970 is illustrated in Figure 7.13. The growth rate was about 4.5% per year for the period, but is expected to slow down to less than 4% for the immediate future. Table 7.15 illustrates the distribution of glass-container shipments by end use.

Materials needs in the glass-container industry are conditioned by the fact that, unlike other packaging materials, glass cannot be shipped as an intermediate raw material to a converter for fabrication. For this reason, the glass producer also produces the container, which is then shipped to the packager for filling, sealing, and shipment. Figure 7.14 shows these characteristics of the industry structure. The volume of major raw-material needs (Figure 7.15) is large: 7.2 million tons of sand, 2.35 million tons of soda ash, and 2.35 million tons of limestone were needed to manufacture the 10.8 million tons of glass containers, representing 37 billion packaging units, produced in 1970. Color can be controlled in nearly all glasses by additions in glassmaking of a variety of compounds. Some colors require or are enhanced by oxidation of the coloring agents. Coating of glass containers is quite common and often involves two layers, for example, titanium oxide followed by a lubricious coating such as polyethylene. Some glass containers (such as for aerosols) have rather thick coatings of a polymer resin for protection against mechanical damage as well as for aesthetic appeal. Thick opaque or translucent oxide and metallic coatings are sometimes applied to provide desired color effects or light protection.

Materials availability does not appear to be a problem for glass containers since, for the present and foreseeable future, there are adequate reserves of the three main ingredients of glass—sand, limestone, and soda ash.

Recycling is readily feasible technically for glass containers, whether as containers or as material, because glass is chemically inert, and does not break down chemically or biologically. However, when bottles and jars are littered, the inertness of the glass means they do not disappear by degradation, but remain visible and can become hazardous wastes. Discarded glass containers do find use as a good aggregate base for construction and in cullet. The latter, which is obtained from two sources: scrap dealers and glass-plant wastes, normally represents between 15 to 30% of the input materials used in glassmaking (the major portion of the cullet comes from the inhouse waste). Examples of direct use of cullet are as a substitute for stone to form a paving material in conjunction with an asphalt binder, and for soil conditioning. A variety of possibilities for secondary uses of glass are technically feasible; their practicality will depend largely on the development of economical collection methods for the discarded and frequently dispersed containers.

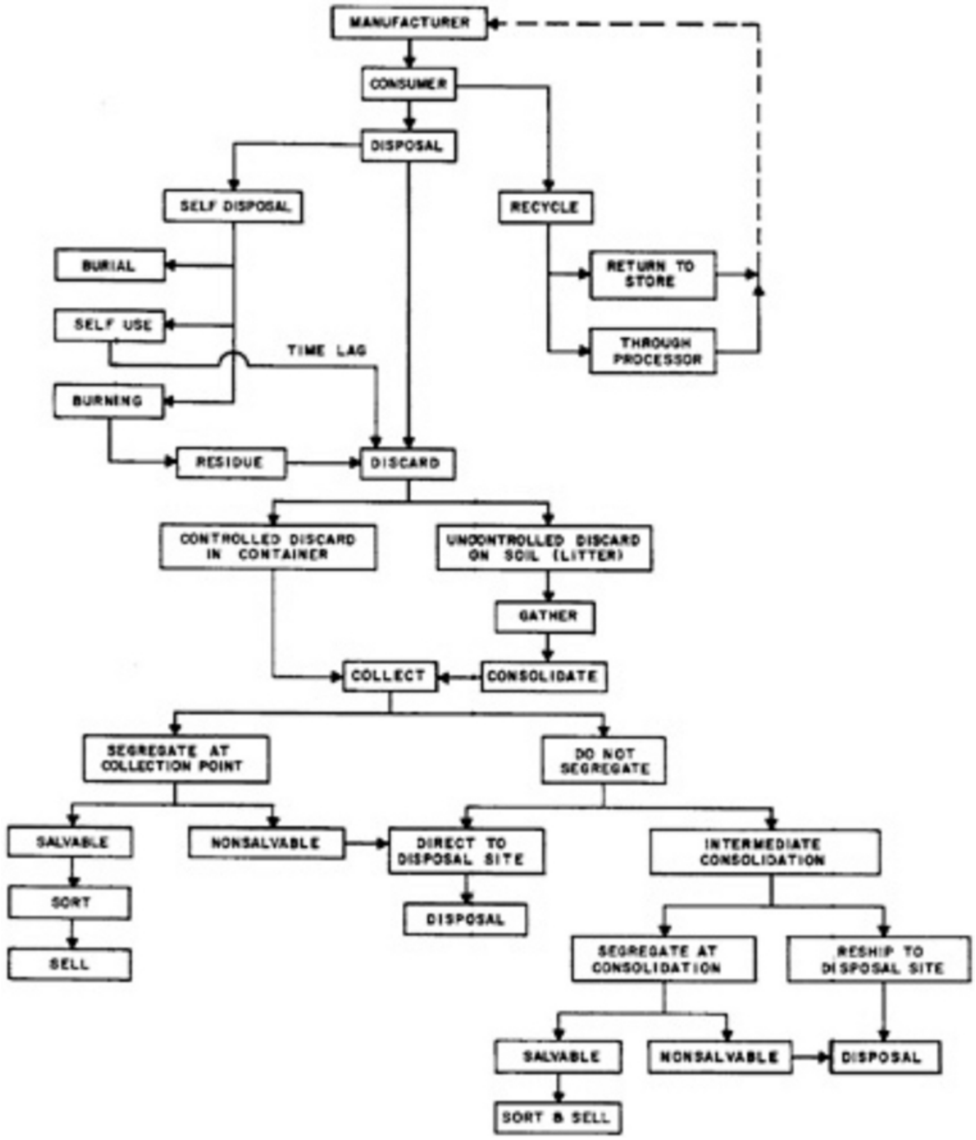


FIGURE 7.12. FLOW OF PACKAGING FROM CONSUMER TO DISPOSAL SITE OR RECYCLE.

FIGURE 7.13 GLASS-CONTAINER INDUSTRY SHIPMENTS millions of gross 1900–1975

TABLE 7.15 Distribution of Glass-Container Shipments by End-Use: 1958 to 1976

								Est.
End-Use	1958	1960	1962	1964	1966	1970	1973	1976
Food	42.9	41.3	40.6	39.5	36.7	32.9	30.7	27.9
Beverage	25.0	27.7	32.5	36.6	40.9	48.8	53.3	58.6
Drug and Cosmetic	23.9	22.5	21.4	19.9	19.6	16.5	14.7	12.6
Chemical, Household, and Industrial	8.2	8.5	5.5	4.0	2.8	1.8	1.3	0.9

FIGURE 7.14 GLASS-PACKAGING INDUSTRY STRUCTURE AND FLOW CHART

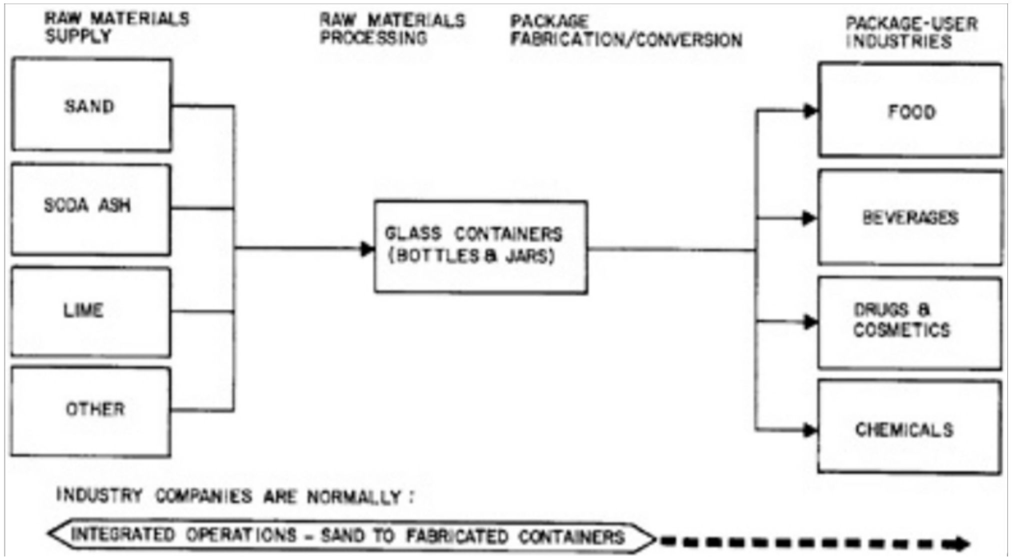
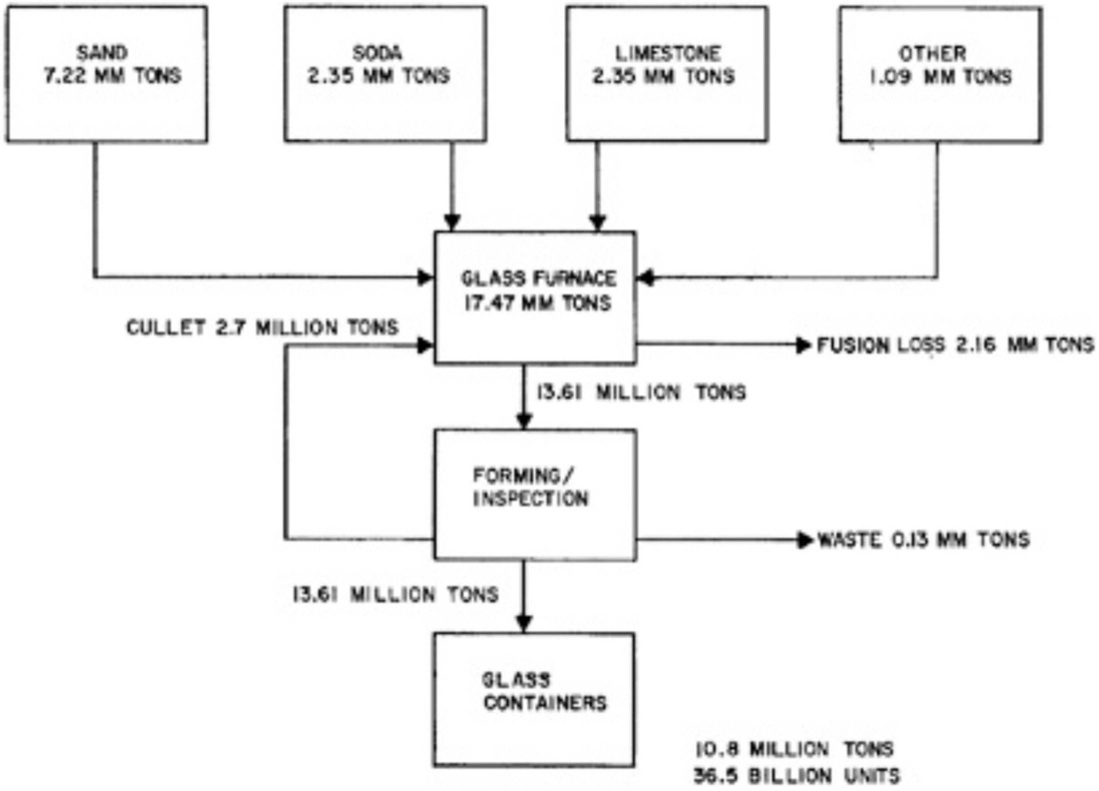


FIGURE 7.15 MATERIALS REQUIREMENTS FOR GLASS CONTAINERS (DATA FOR 1970)



Plastic Containers: The principal materials flows and structural features of the plastics-container industry are illustrated in Figure 7.16. Plastics have some unique performance characteristics in packaging applications which account for their growth. For example, readily formed (blow-molded) plastic containers—especially from nonbreakable polyethylene—have essentially replaced glass jugs for many applications. The volume of plastics in packaging of all kinds has grown to 3.6 billion pounds in 1970. This growth and the major end-uses are shown in Table 7.16.

The materials needs of the industry are derived mainly from the single petroleum and the natural-gas derivatives, ethylene—which is the source of the three major plastics, polyethylene, polyvinyl chloride, and polystyrene (see Figure 7.17). The other major plastic, polypropylene, is obtained from a process by which ethane and propane are produced from natural gas or petroleum fractions. Polyethylene accounted for 61.5% of the volume of container plastics consumed in 1971 or a total of 2.47 billion pounds. Polystyrene packaging utilized 876 million pounds to rank second in usage at 22%. Polyvinyl chloride (PVC) usage was 6.8% or 270 million pounds, and polypropylene accounted for 5.0% at 200 million pounds. The biggest percentage gain in the last five years occurred in PVC, which rose from 4.0% of the market in 1966 to 6.8% of the market in 1971. Another family of plastics whose use is just beginning to take hold is acrylics—which appear promising for soft-drink bottling. The total volume of plastics consumed by the container industry is expected to double in the period 1970–76.

Materials availability is directly related to the availability of the primary raw materials, natural gas and petroleum reserves, and to competition with their use for energy applications. For details, see section on Plastics Industry.

Recycling of plastics from residential and commercial refuse is little practiced at present. In contrast, plastic wastes are collected commercially by scrap dealers from industry, plastic extruders, converters, molders and fabricators—and can usually be completely recycled. However, polyethylene, which accounts for the bulk of packaging plastics, is virtually worthless as scrap at present.

Metal Containers: The flow of the principal materials—in steel and aluminum—in the metals-packaging industry is shown in Figure 7.18. Generally, steel containers are manufactured by independent converters or by packagers from rolled tinplate purchased from the steel industry. In contrast, although aluminum containers account for only a small percentage of total aluminum output (11% in 1969), aluminum producers are also container producers. The distribution of the output of the industry by end-use and its change with time shown in Table 7.17 illustrates the dramatic growth in beverage-can use and decline in nonfood use. Overall, the ten-year rate of increase in cans consumed (1966–1976) is expected to be 3.7% per year.

The materials needs of the industry are significant in scale as shown by the fact that, in 1966, 14.3 billion pounds of metals were converted into packages; 73% being converted into metal cans, which constituted 54.4 billion packaging units. In 1976, over 16.8 billion pounds of metals will be for packaging.

A summary of the quantities of metals consumed in container applications

FIGURE 7.16 PLASTIC-PACKAGING INDUSTRY STRUCTURE AND FLOW

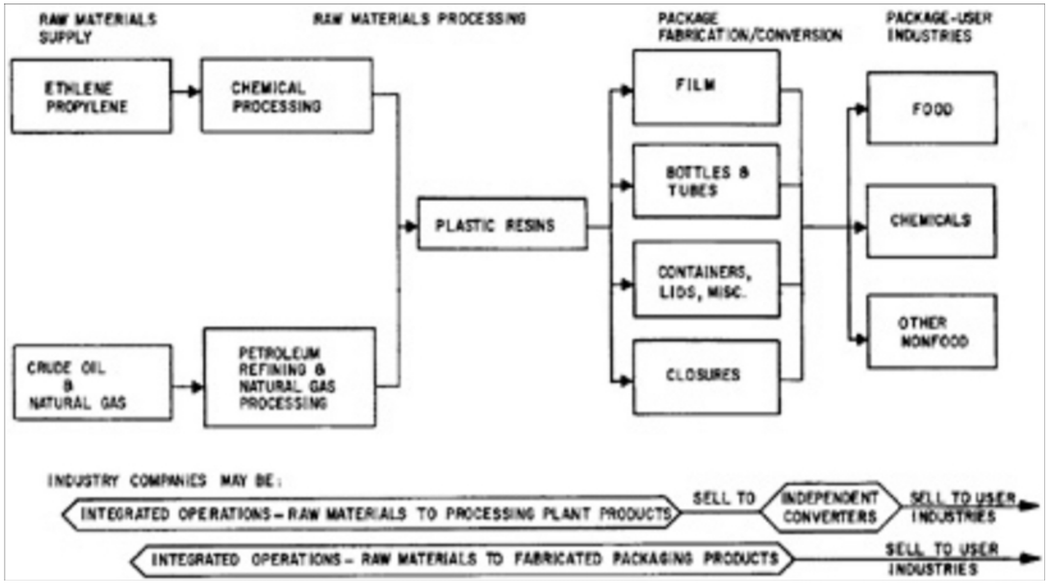


TABLE 7.16 Consumption of Plastics in Packaging by End-Use: 1958 to 1976

	In Millions of Pounds							
								Est.
End-Use	1958	1960	1962	1964	1966	1970	1973	1976
Rigid and Semi-Rigid:								
Bottles	23	65	175	227	304	730	1150	1700
Tubes				3	15	30	35	40
Formed and Molded	61	120	175	288	478	800	1000	1400
Closures	22	22	58	66	85	120	160	210
Total	106	207	408	584	882	1680	2345	3350
Film:	630	776	874	1026	1317	1940	2350	2910
Overall Total	736	983	1282	1610	2199	3620	4695	6260

FIGURE 7.17 PACKAGING PLASTICS COMMONLY DERIVED FROM ETHYLENE

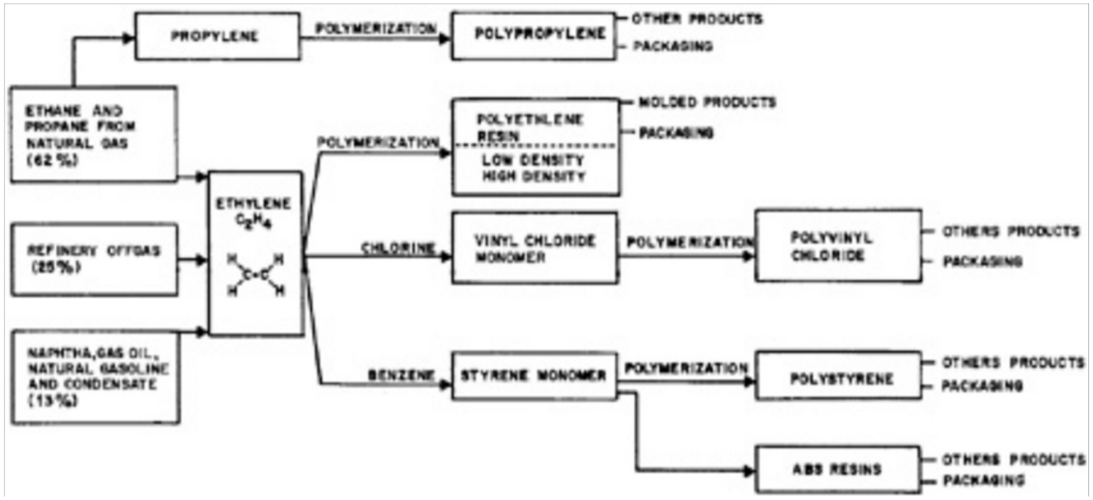


FIGURE 7.18 METAL-PACKAGING INDUSTRY STRUCTURE AND FLOW CHART

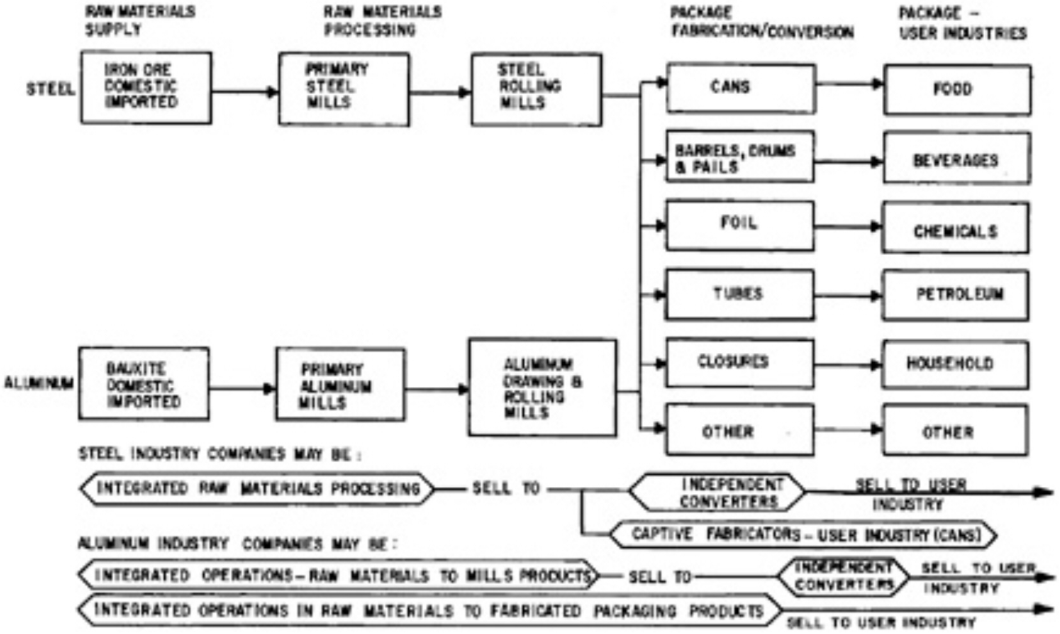


TABLE 7.17 Number of Cans Consumed by End-Use: 1958 to 1976

	Millions of Cans							
						Est.		1966 to 1976 Rate of Change (percent annually)
End-Use	1958	1960	1963	1966	1970	1973	1976	
Foods	25,562	26,513	26,096	26,164	27,190	28,050	28,990	1.0
Beverages	9,685	10,693	12,512	19,557	25,040	30,130	36,860	6.5
Nonfood	6,075	4,288	4,093	4,395	5,010	5,310	5,820	`3.3
Total Metal Cans	43,290	44,373	45,903	54,436	62,210	69,300	78,270	3.7

for 1966 and projected for 1976 is given in Figure 7.19. These relatively flat curves represent an annual growth of about 1.6% for total can production.

Materials availability and costs for the industry present some uncertainties for the future. For steel, although there are large quantities of iron ore in the U.S., the tonnage of imported ore is high and increasing because of lower costs for imported ores. The majority of the tin for the making of tin-plate must be imported since there are no large deposits of tin ore in the U.S. Similarly, large quantities of aluminum and aluminum ores are imported for aluminum cans. For details, see appropriate portions of the section on the Metals Industry.

Recycling of containers has substantial potential, but of the 6.8 million tons of steel which appear in containers every year, only a small portion is recovered. The overwhelming bulk of salvaged materials comes not from post-consumer wastes, but from detinneries who rely on clean clippings from can-production plants for their materials. As with other materials, the economics of collection, sorting, and handling are currently unfavorable for widespread recycling of steel cans. In the case of aluminum salvage, technologies for complete recycle of canning alloy from post-consumer waste have been developed. Although some such recovery is undertaken, the economics are still uncertain.

Paperboard Containers: Paperboard can be divided into five major grades, three of which (containerboard, folding boxboard, and foodboard) represent the bulk of paperboard containers. Table 7.18 shows U.S. production of paperboard (by total and major grade) for 1960, 1966–70, and Figure 7.20 illustrates the flow of materials in the industry.

Containerboard is the largest grade of paperboard produced, currently accounting for about 60% of total board production. Its primary use is in the manufacture of corrugated and solid fiber boxes, more than 51% of the total output going to three consuming industries: food and beverage, 29%; paper and paper products, 13%; and stone, clay, and glass, 10%. Folding boxboard is employed almost exclusively in the manufacture of folding cartons, which are printed, cut, creased, glued, and then shipped flat to the packager who sets up, fills, and seals the carton. Folding cartons are relatively inexpensive, can be manufactured at high speeds, and are economical relative to transportation and storage costs. The final major grade, foodboard, is used exclusively to manufacture such sanitary paperboard containers as milk cartons, frozen food containers, meat trays, and ice cream cartons. About 85% of the pulp used in its manufacture is bleached or semibleached kraft. The boards are sized for water resistance and are frequently coated, particularly for applications that require high quality printing. Since 1960, the production of foodboard has been growing at an average rate of around 5% per year.

As more of the primary producers integrate forward into finished products, paperboard and its converted products are increasingly becoming one single industry. In 1967, integrated firms (those with converting plants taking 50% or more of a company's paperboard output) produced 89% of all containerboard and 61% of all folding boxboard. The industry is also becoming highly concentrated. In 1967, of 135 companies reporting to the Paperboard Group of the American Paper Institute, the top ten accounted for 44% of sales; the second ten, 20%; and the third ten, 12%.

Materials needs for the industry are met from wood and waste paper. In

FIGURE 7.19 CONSUMPTION OF METAL IN PACKAGING

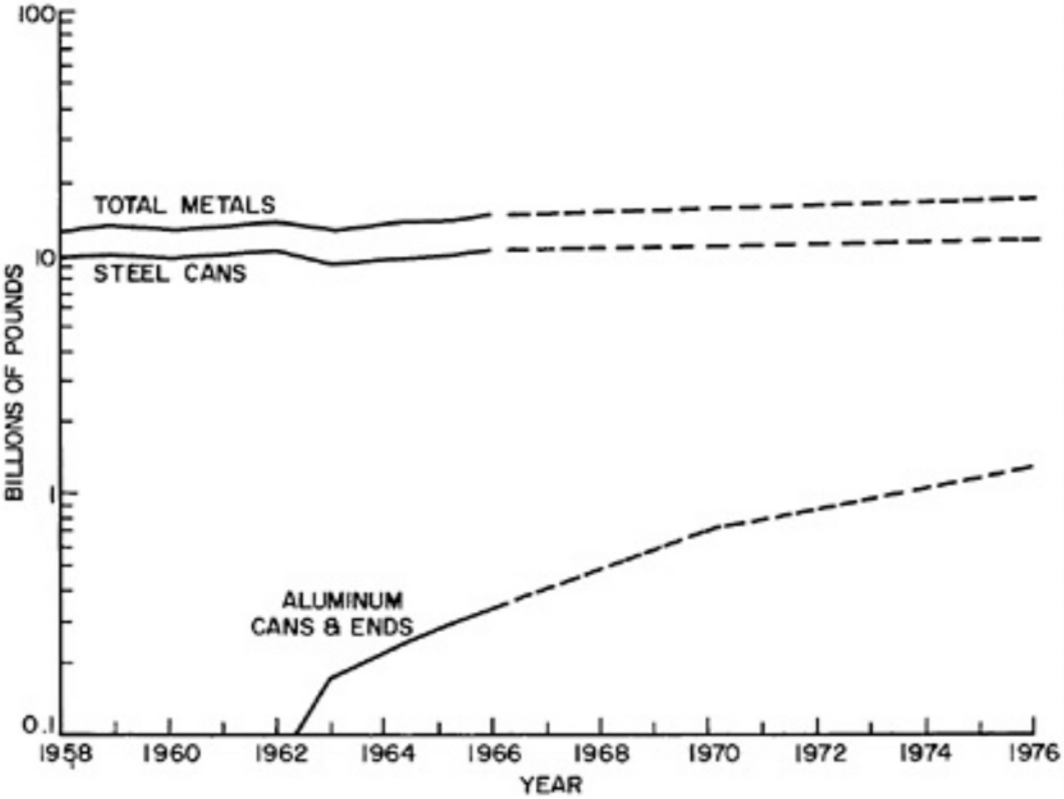


TABLE 7.18 U.S. Production of Paperboard by Grade (Million Tons) 1960, 1966–1970

	Containerboard	Folding Boxboard	Special Foodboard	All Other*	Total
1960	8637	2923	1447	2920	15927
1966	13661	3614	1902	4002	23179
1967	13428	3575	1902	3914	22819
1968	14846	3739	2076	4243	24904
1969	16131	3779	2147	4319	26376
1970	15805	3559	2211	3919	25494

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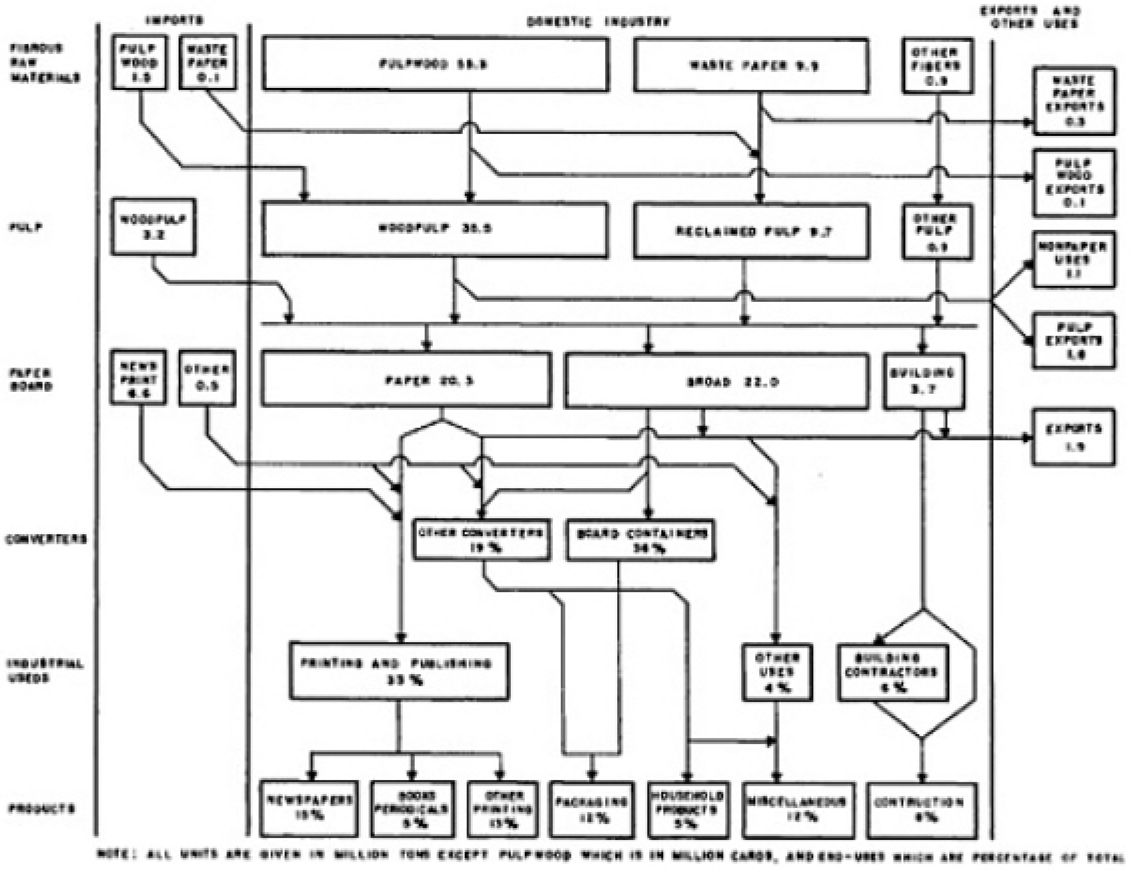
* All other includes exports of folding boxboard and foodboard.

FIGURE 7.20 THE PAPER, PULP AND PAPERBOARD INDUSTRY 1967



1967, wood accounted for 78% of the total and waste paper 20%. Minor amounts of cotton linters, straw, and bagasse are also used. Pulpwood of suitable species and in the form of logs (round-wood) or chips is the raw material for woodpulp in paper manufacture. In 1967, 55.3 million cords, on a rough-wood basis, were consumed by the industry. Waste materials in the form of chips or residues, the by-products of sawmills, plywood plants, and other wood-using facilities, provide a substantial amount of the paper industry's pulpwood; in 1964, 11.2 million cords, or 23% of the 48.5 million cords of pulpwood produced, came from such residues. This is up from 8.6% in 1955, with 1970 estimated at 25%.

Waste paper in a salable condition for pulping is the second major raw-material source. The amount of waste paper used varies substantially by grade of product. In the paperboard segment of the industry, the range generally falls between a low of zero (foodboard grades) and a high of 70–80% (boxboard).

Materials availability is illustrated by the data in Table 7.19, which represents the total commercial forest land area in the U.S., 509 million acres. The major portion of the commercial forest area (59%) is owned by farmers and individuals, while governmental agencies control the next largest amount, 28%. The forest industry controls the balance, amounting to 13% of the total, or 67 million acres. The southern states have the greatest concentration of commercial forest area and also the largest volume of timber harvested annually.

Recycling is significant in the paper industry, but three-fourths of the waste paper recycled is derived from waste sources other than packaging wastes. However, paperboard mills consume about 75% of the waste paper recycled. The only paperboard-packaging material which plays a significant role in paper salvage is corrugated containers. An estimated 2.5 million tons of these containers were recycled in 1966 and amounted to 20% of the 12.5 million tons of containerboard produced that year. The other paper-packaging materials are usually ignored by salvage operators because corrugated paperboard is more readily available in significant quantities, easily separated, and not as likely to be contaminated as other paper wastes usually are. Recent governmental decisions to encourage recycling by purchasing only paper products that have a specified percentage of recycled paper could induce industry to increase use of waste paper in order to capture this portion of the total market. However, this shift may increase costs until such time as systems and processes are developed which will increase availability and allow waste fiber to compete with virgin fiber.

Automobile Industry

The activities of the automobile industry have broad influence on the nation's economy. Table 7.20 illustrates this point with respect to the extent to which other industries contribute to automotive production. In 1967, these other industries employed nearly 500,000 workers to produce over $13 billion worth of automotive parts. In 1970, with automotive sales at $18 billion, employment by the automakers themselves was 364,000. The gross auto product of about $31 billion in 1970 accounted for 3% of our Gross

TABLE 7.19 Commercial Forests of the United States—509 Million Acres. Historical and Projected Timber Harvest, Growth, and Inventory

	Growing Stock in Billion Cubic Feet		
Year	Harvest	Growth	Inventory
1952	10.8	14.3	595.8
1962	10.1	16.3	627.9
1970	11.5	17.4	671.9
1980	13.7	18.2	727.7
1990	16.9	17.2	757.9
2000	21.6	17.2	738.3

TABLE 7.20 $13 Billion Automotive Parts Produced in Other Industries*

Industry Producing	Automotive Shipment (Millions)	Estimated Automotive Employment
Narrow Fabrics	$ 19.3	1127
Tufted Carpets and Rugs	84.9	1876
Padding and Upholstery Filling	60.1	2327
Tire Cord and Fabric, Total	404.6	9201
Apparel Findings and Related Products	513.0	20196
Fabricated Textile Products, n.e.c.	98.0	4904
Public Building and Related Furniture	61.4	3300
Die-cut Paper and Board	41.9	1451
Paints and Allied Products	218.0	4959
Tires and Inner Tubes, Total	2793.8	69430
Fabricated Rubber Products, n.e.c., Total	320.2	14443
Plastic Products, n.e.c.	58.4	2768
Flat Glass, Total	342.0	12900
Pressed and Blown Glass, n.e.c.	17.1	808
Glass Products made of Purchased Glass except Laminated	100.8	3708
Asbestos Products, Total	142.4	5282
Hardware, n.e.c.	807.7	34303
Fabricated Plate Work, Boiler Shops Products	27.1	964
Screw Machine Products	233.2	11172
Bolts, Nuts, Rivets, and Washers	91.2	3696
Metal Stampings, Total	3178.2	121760
Miscellaneous Fabricated Wire Products	153.0	7525
Steel Springs, Total	164.2	6568
Internal Combustion Engines	233.2	7071
Refrigeration Machinery	531.3	16211
Machine Shop Products, Total	347.7	20453
Electrical Measuring Instrument	2.7	123
Motors and Generators, Total	145.6	6881
Carbon and Graphite Products	12.2	488
Electric Lamps (Bulbs)	88.2	3334
Lighting Fixtures	186.1	7555
Radio and TV Receiving Sets	211.1	6418

Industry Producing	Automotive Shipment (Millions)	Estimated Automotive Employment
Radio, TV Communications Equipment	412.6	12675
Electronic Components, n.e.c.	22.2	1256
Storage Batteries, Total	395.8	13221
Electrical Equipment for Internal Combustion Engine	996.7	40442
Mechanical Measuring Instruments	92.7	4666
Total Automotive Products	$13638.6	492375

* This is an Incomplete tabulation in that it contains only those industries for which automotive parts were shown by the 1967 Census of Manufacturers.

NOTE: Automotive employment is estimated by the Automobile Manufacturers Association, by assuming that such employment in these industries is in direct proportion to the ratio of automotive shipments to total shipments of the industry.

1971 Automobile Facts & Figures, p. 39, Automobile Manufacturers Assn.

National Product, and automotive employees accounted for 5% of all manufacturing employees.

Materials usage in the industry represents a significant fraction of annual U.S. consumption of a variety of basic materials because of the large number of vehicles involved and their large individual mass. A typical 1970 four-door sedan contains over a ton and a half of metals, 150 pounds of plastics, 200 pounds of other polymers, and 100 pounds of glass (see Table 7.21). The total consumption of selected metals by the automotive industry in 1969 is shown in Table 7.22 compared to their U.S. consumption. In addition to these and other metals, the automotive industry accounted in 1969 for 65% of the national consumption of rubber, and over 2% of the national cotton production.

The economic significance of materials processing technology in this industry is indicated by the fact that roughly $500 worth of raw materials is transformed into a car worth at least $3,500 in functional value, and that materials-related costs are a significant portion of this chain of value-added manufacturing steps. Since less than 30% of the automobile units manufactured in the world are made in the U.S., competition for the necessary materials is world-wide.

Materials availability is an important question for this materials-intensive industry. Table 7.23 shows that a large fraction of the principal metals in an American automobile now comes from foreign sources, a situation that contributes negatively to the U.S. trade balance and hence must be viewed cautiously—politically as well as economically. The large scale of materials consumption in the automotive industry is a key factor to be taken into account in every product improvement decision. Adding just one pound per vehicle adds some 5,000 tons to the total materials requirement for the U.S. industry. Thus, new materials must have an assured availability in addition to offering cost, performance, and other advantages.

Materials conservation, scrap utilization, and recycling in the automotive industry are making substantial progress in their degree of application. Currently, more than 90% of the output of the automotive cast iron foundries is made up of recycled iron. Approximately 88% of all cars junked each year (6 to 7 million) are recycled into the scrap and iron industries. In automobile manufacture, the bulk of the scrap produced is metal and, because there is strong economic incentive to do so, almost 100% of this metal scrap is reused or reclaimed. The flow of materials with respect to recycling in the industry is described in Figure 7.21 which shows that of the total ferrous metals entering the automotive manufacturing cycle, 65% comes from steel mills; 20% comes in the form of castings from automaker foundries; and 15% from inhouse scrap. In processing these ferrous materials, approximately 70% appear as part of the finished products and some 30% are scrap materials. The latter come in many grades and classifications, numbering as many as 20 or 25. Examples include: No. 1 bundles, flash turnings, borings, bushelings, clips, and such alloyed materials as stainless, galvanized and lead-coated sheet steel.

Solid wastes also arise in the industry from nonproduction materials, i.e. materials not incorporated in the final vehicle, but necessary for the manufacturing processes. Increased efforts are underway in the automotive industry to handle the millions of tons of solid waste involved. For the most part,

TABLE 7.21 Materials in Typical 1971 Four-Door Sedan

Materials	Net Weight (Lbs.)	
Metals		3400
Steel	2500	
Iron	750	
Aluminum & aluminum alloys	50	
Copper & copper alloys	40	
Zinc & zinc alloys	30	
Lead & lead alloys	30	
Plastics		150
Styrene plastic	10	
Olefin plastic	20	
Vinyl plastic	30	
Thermoset molding	15	
Other thermoset plastic	15	
Plastic foam materials	35	
Nylon	25	
Other Polymers		200
Paper	20	
Paints & coatings	10	
Rubber compounds (including tires)	170	
Glass		100

TABLE 7.22 Selected Automotive Metals Consumption, 1969

	U.S. Total Consumption (tons)	Automotive Consumption (tons)	Automotive Percentage
Steel	93,876,871	18,276,409	20
Iron	17,081,299	3,199,456	19
Aluminum	5,383,500	534,000	10
Copper	2,454,500	287,500	8
Zinc	1,588,000	517,746	33
Nickel	210,000	23,500	11

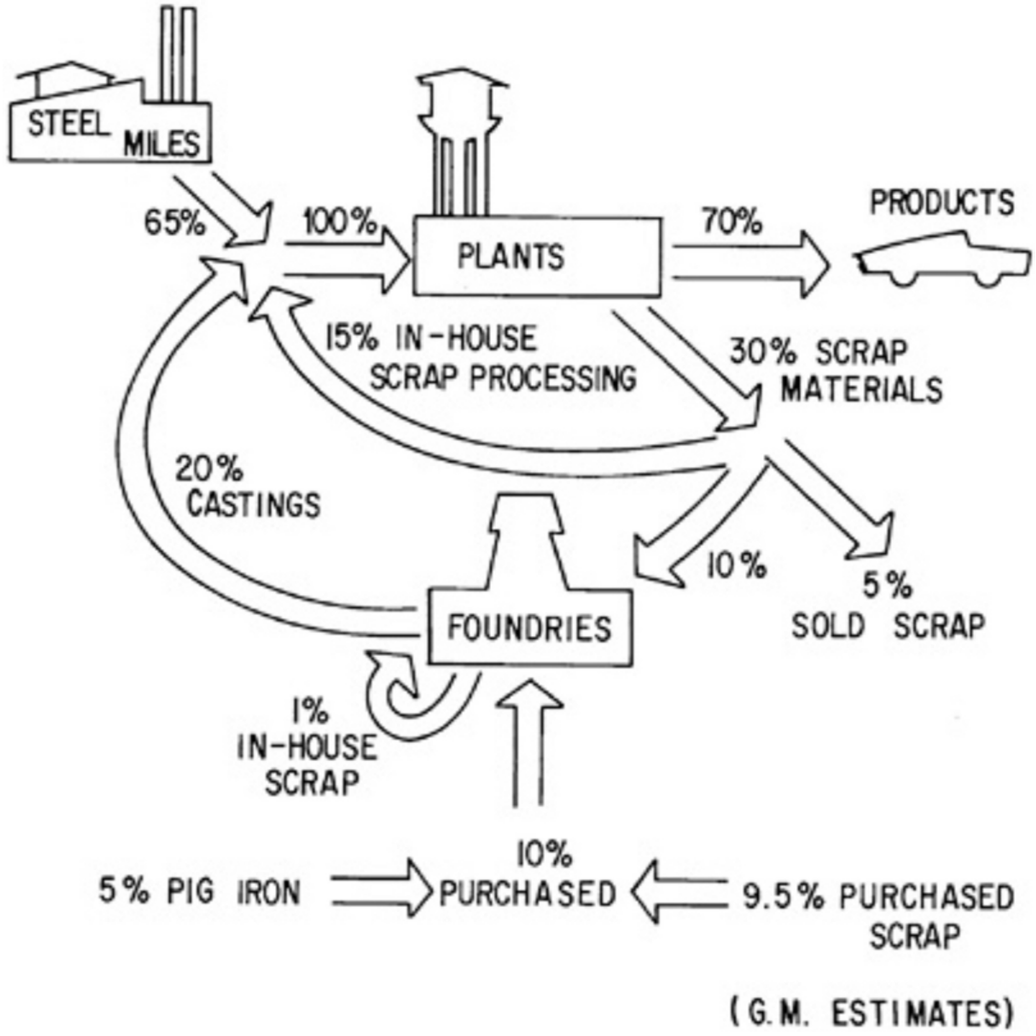
Source: 1971 Automobile Facts and Figures, p. 25

TABLE 7.23 Foreign Ores in a U.S. Automobile

Metal	Total Pounds	Pounds of Foreign Metal	Percentage of Foreign Metal
Iron	3,705	1,334	36
Copper	52	20	38
Lead	24	14	58
Aluminum	48	44	89
Zinc	123	77	59

Source: B.Eastland, Division of Research, U.S. Atomic Energy Commission.

FIGURE 7.21 RECYCLING OF FERROUS MATERIALS IN AUTOMOTIVE INDUSTRY 1970'S



inert solids are deposited in sanitary landfills because reclamation or recycling is either impractical, or uneconomical, or both. Fly ash, for instance, can be used as an aggregate in cinder blocks or as a secondary road-surfacing material. However, the supply far exceeds the current demand. Core sand from foundries can be reclaimed, but costs substantially more than new sand. Likewise, construction debris—mostly broken concrete, brick, and dirt—has little value worth reclaiming at present. All of these materials are inert and, consequently, can be utilized in sanitary landfills without harmful effects.

Some of the solid wastes are byproducts of air- or water-pollution abatement. For example, phosphating materials, used as a rust inhibitor prior to painting steel surfaces, are distributed in sanitary landfills where they actually can improve the soil through the minerals they provide. Much of the remaining types of solid wastes are being reclaimed. The automobile industry estimates that at least 50% of the paper, cardboard, and wood wastes are being reconstituted. In addition, there are vigorous programs underway to reduce the volume of these disposable materials in interplant shipments through greater use of returnable containers and more skillful packaging of production parts.

Reclamation of the automobile after-use is an extensive industry. Of the 20 million junk cars in the U.S. today, nearly 16 million are in the inventories of auto wreckers and scrap processors. Most of the 6.5 million cars that are taken off registration lists each year find their way into auto-wrecker yards and scrap-processing firms where they are eventually recycled into usable scrap for steel mills and foundries.

Competition among materials is especially strong in the automotive industry. Where once only one material could do the job, there are now many materials offering similar performance at competitive prices. As a case in point, the application of plastics in automobiles has grown considerably because they now offer both unique and improved engineering properties at lower costs; for certain parts, a pound of typical automotive plastic goes about seven times as far as a pound of metal. Table 7.24 shows the relative costs of three metals and three plastics by weight and volume. In general, it is more economical to use engineering plastics than metal where the required volume of material is roughly equal. The resulting weight reduction is becoming of increased importance as safety and emissions-control features add to the weight of cars.

The substitution of plastics for steel, aluminum, and zinc has been a trend for years in the automobile industry. Automotive consumption of plastics and other polymers grew from 300 million pounds in 1965 to about 1 billion pounds in 1971. Today the list of commercially available polymers includes some 50 different plastics. Low tooling costs and design flexibility are major reasons for the use of plastics. Complex shapes may be fabricated in single operations. While cost is an important factor in materials selection, it turns out that better performance, durability, and safety are frequently the reasons for choosing plastics. Many parts found on current model cars involve materials with a cost penalty to solve other problems; included are certain applications of plastics as well as electroplates, paint, and galvanized steel. For injection-molded plastics alone, automotive consumption has risen from 64 million pounds in 1963 to 364 million pounds in 1970; by

TABLE 7.24 Comparison of Material Cost*

Material	Cost per pound (cents)	Density (lbs./cu.in.)	Cost per cu.in. (cents)
Steel	10	0.283	2.8
Aluminum	25	0.100	2.5
Zinc	20	0.236	4.7
ABS	30	0.038	1.1
Polypropylene	25	0.033	0.8
Polyvinyl chloride	28	0.045	1.3

* Approximate 1970 prices, intended for comparison purposes only.

1975 this figure is expected to double. A tally of injection-molded plastics replacing metal would include such things as grilles, instrument panels, front-ends, fender extensions, fender liners, lamp housings, bezels, and valence panels.

Besides plastics, other polymers are of major importance to the automotive industry, such as elastomers, paints, fabrics, adhesives, and sealers. Whereas a 1950 car used about 10 pounds of adhesives and sealants, today's car carries about 70 pounds. In a typical full-size car of 1971, there were as many as 750 rubber parts in addition to the tires; these were made from 30 different rubber compounds. Since 1970 several significant milestones in nontire applications of rubber compounds have been achieved by the automobile industry. Some examples are elastomer tapes for bond-welding of large structural components, spray-on polyurethane bumper coatings, and the all-foam seats of polyurethane. Urethane coatings are being employed in production to coat elastomeric bumpers, instrument panels, and polycarbonate headlight bezels. Such coatings are ready for use on integral skin-foamed parts such as steering wheels, arm and head rests, visors, air scoops, and strip moldings. Urethane coatings also show promise for hoods, air foils, bumper guards, and fender extensions. The use of polyurethane foam is expanding faster than that of any other material in the automotive industry. More than 60% of all 1972 model cars had adopted the all-foam seat in favor of the once-dominant springs and padding.

Penetration of plastics into the markets for steel, aluminum, and zinc is underscored by the differences in the growth-of-the-demand for these materials during the 1960's. While plastics production increased over 150%, from 3 to 8 million tons, the 10-year increase in steel production was 33%, aluminum 60%, and zinc 25%. Some of the automotive products where this competition is important are listed in Table 7.25.

Certain trends for plastics versus metals in the 1970's are already evident. The average car in 1969 had approximately 100 pounds of zinc and 100 pounds of plastics. However, the use of zinc is expected to decline. Auto parts for which zinc and plastics compete include grilles, instrument panel assemblies, headlight and taillight housings, air-intake cowls, door glass channels, radio speakers, glove-box doors, bezels, trim components, etc. Usually the choice between plastics and zinc is settled by some secondary consideration such as appearance or style. The difficulty of plating plastics has favored zinc in some applications. In 1970, some automakers returned from plastics to zinc for rear-fender extensions, taillight assemblies, and headlight assemblies. Zinc is finding new automotive uses which cannot be challenged by plastics. In recent years, zinc has doubled the life of automobile leaf springs by acting as a sacrificial metal for corrosion.

The continued development of plastic composite materials, especially those reinforced with glass fibers, hold even more promise for increasing the automotive uses of plastics. These materials form a unique bridge between the limitations of metals on the one hand and of unreinforced plastics on the other. Their favorable economics, rapidly advancing processing technology, and good mechanical performance assure their successful application in many areas which previously relied upon fabricated steel, die-cast metals, and expensive engineering thermoplastics. There have been more developments in glass-reinforced plastics in the five years of 1965–70 than in all the previous

TABLE 7.25 Automotive Products That Can Be Made of Either Plastic or Metal

Automotive Body Components	Radiator Grilles
Fuel Tanks	Instrument Cluster Panels
Front Seat-Back Trim Panel	Wheelcovers
Radiator Fan Shrouds	Cowl Kick Panels
Front Fender Skirts and Liners	Seat Grid Liners
Truck Trailer Liners	Ductwork for Heating, Airconditioning
Door Inner Panels and Locks	Plated Trim, Decorative Medallions
Control Handles and Knobs	Bezels, Shelves, Mirror Supports
Glove Compartment	Arm Rests, Sun Visors

years since their introduction in the 1940's. With new matched die-molding processes, for example, these materials may now compete with steel in large production runs of up to 70,000 units per year. Previously, even half that number could not be run. Current reinforced-plastics production of about one billion pounds per year seems small beside steel's 250 billion pounds, plastic resin's 19 billion, and aluminum's 9 billion. However, a fourth of this business is already in ground-transportation markets, a sector where the high-strength, light-weight and good chemical resistance of reinforced plastics will make them increasingly attractive.

Auto equipment is now the number two consumer of glass-reinforced plastics, after marine equipment, but will probably take over as the top user in the near future. Auto and truck applications alone were up 36% in 1971. In 1972 at least 250 different applications of glass reinforced plastics were used, compared to 200 different applications in 1971 and 110 in 1970. Car models in 1971 employed glass-reinforced plastics in 13 instrument panel assemblies compared to 8 in 1970. In 1972 model cars, there were 150 different applications of injection-molded glass-reinforced thermoplastics alone, compared to 92 in 1971 and 60 in 1970. In almost all cases, injection-molded reinforced thermoplastics now have strength and modulus values higher than die-cast zinc. A complex composite which can be injection molded for large automotive components, such as consoles, bucket-seat backs, and instrument panels, combined reinforced polystyrenes with fiberglass-reinforced styrene-acrylonitrile copolymer. Recently, a new glass-fiber-reinforced foamed plastic has become available; it is as strong as conventional reinforced plastic but weighs only 66% as much. Also, this fiber-reinforced foam can be injection molded. In addition, new processing techniques for reinforced thermoset plastics are improving these materials as candidates for automotive parts.

Sheet-molding compounds were first introduced in 1969 in Chrysler station-wagon air deflectors. Usage has already spread, growing from 0.4 million pounds in 1969 to 10 million pounds in 1971, including front exterior panels, hoods, valence panels, window insert frames, and fender skirts. Large and complex pieces, having molded-in ribs, inserts, bosses, threads, and wide variations in thickness across the section, can be molded in one operation. If many of the one-piece sheet-molded front panels had been made of metal, they would have required six or seven pieces with as many as 20 forming and assembly operations.

There has also been substantial growth in aluminum usage in the automotive industry. A versatile engineering material, aluminum alloys have seen increasing applications that take advantage of their high strength-to-weight ratio, impact resistance, corrosion resistance, and heat conductivity, competing with iron and steel. The lighter weight of aluminum in comparison to cast iron has led to its wider adoption in engines. One materials breakthrough is the production-die casting of hypereutectic aluminum-silicon alloy in engine blocks; this eliminates the use of ferrous cylinder-wall liners. Other structural applications of aluminum include wheels, brake drums, optional aluminum cabs on heavy trucks, and the use of high impact-strength aluminum alloys in experimental bumpers and safety vehicles built for the government. The corrosion resistance of aluminum has been used to advantage in chemically brightened or anodized alloys for such production items as grilles, head-lamp bezels, and hubcaps. Its thermal conductivity puts aluminum in competition with copper and brass for automobile air-conditioning and radiator applications, and with iron as well for disk and drum brakes. One British-made aluminum radiator, for instance, is put together with adhesives and uses no fluxes. While aluminum is replacing cast iron, steel, and copper for some parts, lighter magnesium may also replace aluminum. One German-made car, for example uses die-cast magnesium in gearbox casings and engine crank-cases.

All-in-all, 1970 automobiles had a record average of 78 pounds of aluminum, about a 6% gain over 1969 models. This was the fifth straight year of growing use of aluminum in U.S. cars, and a 50% gain over a decade ago.

Developments in other materials than plastics and the light metals continue to be important in the automobile industry. Steels of recent vintage which have had large influence in the field include galvanized steels, whose automotive uses quintupled in the last decade; steels with other improved coatings and finishes, and higher-strength steels. HSLA steels (meaning “high-strength, low-alloy”) used in 1972 bumpers, for example, have yield strengths of about 45,000 psi, compared to about 30,000 psi for carbon steel bumpers. HSLA steels for side-impact beams are said to have a yield strength of 75,000 psi. Pre-painted and pre-primed steels also are becoming more readily available, and for some hard-to-form parts, pre-painted steels may be a better choice than even galvanized steel.

Ceramic ferrites, usually pressed and sintered metal-oxide powders, are often improved substitutes for more expensive magnets in radios, small motors, and other electronic devices. Ferrites are now finding application in the small motors which raise and lower car windows, lock doors, and operate windshield washers. They are also used extensively in radios, a product for which automobile sets comprised 49% of the 1969 U.S. production.

The competition among materials has also resulted in new composite materials which use, sometimes synergistically, the best qualities of each material. Thus, the first production bumper to withstand 4-mph barrier impacts without damage (1972 Saab 99-E model) took advantage of the properties of three materials—rubber, steel, and plastics. Under a thick rubber exterior coating, a U-shaped steel compartment holds energy-absorbing cellular plastic blocks.

The role of processing technology has proved critical to production efficiency in the automobile industry. Metal casting, cold forming, and powder metallurgy are of growing significance in the industry and illustrate the impact, real and potential, of advancing metal-processing technology. For example, a new die-casting process along with a new aluminum alloy have been combined to produce the first all-aluminum engine. Also, a more ductile form of cast iron—nodular iron—has spurred ferrous-casting technology; lower-cost castings with at least equivalent performance are now supplanting parts that were previously forged. Similarly, greater uses of cold-forming processes and powdered-metal parts are resulting from interest in more efficient utilization of materials and reducing scrap. A cold-extrusion application has resulted in an 84% savings in materials over the previous machining process. One automaker has begun production of pole shoes for cranking motors in 1972, employing a new process that converts recycled metal scrap into fine powder.

Powder-metal compacting operations lend themselves naturally to process automation; now automatic presses achieve production rates of 500 to 1500 parts per hour or more. Few processes offer such precise control over materials and properties as does powder metallurgy. Frequently, no secondary-finishing operations are needed and powder-metal parts may be shipped directly following sintering.

In the case of thermoplastics a relatively new development is injection molding using a reciprocating screw. Comparing two machines of similar size, a particular ram-injection unit processes some 80 lbs. of polystyrene per hour, whereas the screw unit processes 200 lbs. per hour. Moreover, materials which are otherwise very difficult to process can now be formed into intricate shapes and heavier moldings. Extrusion is used for forming rods, tubes, films, and shapes in a wide variety of profiles. An example of the extrusion process is in the fabrication of vinyl insulation on automotive electrical cable. Vacuum forming is widely used to shape the thermoplastic skin of dash pads before they are filled with polyurethane foam.

Building Industry

The building and construction industry is among the largest in the nation in terms of contribution to the Gross National Product, amounting to about $109 billion in 1971. As shown in Table 7.26, the total industry has doubled in scale over the past decade. Among the various sectors, buildings, in contrast with heavy construction such as dams and highways, account for the largest share (about 85%) of this total.

The building industry has characteristics which make it quite unique, and therefore difficult to examine for a specific concern, such as innovation in materials technology, without some understanding of its complexities. In particular, markets are too small and heterogeneous for any standardized construction approach even in large production facilities, institutional structures, commercial buildings, and any special class of dwelling. Further, the different types of buildings are variously financed, built, marketed, and used. The industry has been described as composed of more than 90,000 contractors and 1,500,000 subcontractors employing 3,500,000 people. They are supplied by a myriad of other industries employing large numbers, such as the 240,000 employees of sawmills and planing mills, the 160,000 in millwork and related products, and the 260,000 who manufacture equipment. To handle financial, insurance, and real-estate dealings requires another 1,100,000 persons of whom more than 600,000 are in real estate alone. The building-design professions include 30,000 registered architects, and 75,000 engineers plus a number of specialists. The character of this industrial structure and distribution process exercises major influence on technology decisions.

Materials constitute a relatively small part of the total costs of building development; land development, labor, and long-term financing costs are as, or more, important. However, in many instances, the intimate relationship of materials with people and function in buildings has psychological significance as well as physical, economic, and social requirements. Thus, there is real concern for improving materials durability, maintainability, utility, and their aesthetic effects. This concern increases the

TABLE 7.26 New Construction ($ Billions)

	Total	Residential	Utilities Etc.	Commercial	Highways	Educational	Industrial	Hospital
1960	53.9	22.7	5.4	4.2	5.4	3.4	2.9	1.0
1961	55.4	22.7	5.1	4.7	5.9	3.7	2.8	1.1
1962	60.0	25.2	5.1	5.1	6.4	3.6	2.8	1.3
1963	64.6	27.9	5.4	5.0	7.1	4.2	2.9	1.5
1964	67.4	28.0	5.7	5.4	7.1	4.5	3.6	1.8
1965	73.4	27.9	6.5	6.7	7.6	5.0	5.1	1.9
1966	76.0	25.7	7.5	6.9	8.4	6.3	6.7	2.0
1967	77.5	25.6	8.4	7.0	8.6	7.0	6.1	2.0
1968	86.6	30.6	9.7	7.8	9.3	7.0	6.0	2.3
1969	93.3	33.2	10.2	9.4	9.3	6.9	6.8	3.0
1970	94.3	31.7	12.1	9.8	10.0	6.5	6.5	3.4
1971	109.0	42.4	13.5	11.6	10.8	6.5	5.4	3.8
1972E	122.5	49.5	15.3	14.0	12.0	6.6	5.3	4.5
1976E	155.0	56.0	22.5	18.0	15.0	8.0	7.5	7.0

importance of materials to the marketability of the building, which offsets to a degree the relative insensitivity of materials technology in influencing the total cost.

There are a few materials that are produced exclusively for building purposes, and many of the materials industries already discussed are the producers of either raw or processed materials for use in buildings. In addition, buildings contain subsystems—electrical, mechanical, and structural— whose basic material and components may have numerous nonbuilding uses as well. Consequently, the products and problems of other industries are inextricably intertwined with those in the construction industry. Further, the buildings embrace furniture, tools, machines, and other goods, and require an array of community services from waste handling to streets, earth-moving equipment, and soil stabilizers. In a larger sense, all of these involve materials and products which are part of the industrial system.

Due to the highly competitive nature of the building market, walls, floors, partitions, mechanical and electrical subsystems, appliances, stairs, and other elements in buildings have been constructed of a wide variety of materials and combinations thereof, depending upon local building-code requirements, marketability, availability, and the impact of the selected materials on the total cost of the building. As new or improved appliances, fixtures, elevators, air-conditioning systems, structural and nonstructural systems are introduced for the first time, materials usage is directly affected. With almost every type of change—design, functional, technological, economic, ecological, social, legal, or political—materials usage is again influenced.

Factors Affecting Materials Science and Technology: One of the most significant factors in the building industry has been the relatively rapid increase in the ratio between the cost of job-site labor and material cost. The percentage of material in the total “brick and mortar” cost has been decreasing: in multifamily-housing construction, for example, it is now less than 50%—reversing the previous historical relationship. It is believed that this reversal is also the case in many types of nonresidential construction, although detailed studies to establish historical trends are lacking. For some years, labor for all categories of construction have been rising at a rate about twice that of materials prices. While material price increases were reduced during the recent period of price controls, wage rates continued to climb.

It is difficult to determine what portion of increased onsite-labor costs is due to higher “wages” and what portion is assignable to observed lower productivity. The issue of productivity in the industry has been recognized nationally as a major problem; it has been argued that low productivity, even more than high wages, may be pushing the cost of construction beyond the reach of many potential markets.

This trend of increasing onsite labor cost has been largely responsible for the growing emphasis on the production of more and more building components and subsystems in the factory, with its present and traditional lower wage rate and more efficient production processes. For example, several companies produce modules for single-family homes and town houses, and also some of the major subsystems for multifamily housing. Factory-fabricated subsystems and precast-concrete structural subsystems have been adopted for many years in nonresidential construction. However, the full potential of materials is not yet being realized in that for most factory-produced house modules, prefabricated structural components, or factory-built major subsystems, the basic materials of construction are not significantly different from those employed onsite to produce the same basic end facilities. Likewise, since materials may also lower onsite-labor costs, the potential of materials technology for achieving onsite productivity gains must be as much as in-factory gains.

The relationship between labor and material prices is especially relevant in the context of total construction and development costs. For instance, approximately one-third of the total development costs for typical multifamily housing is accounted for in the aggregate cost of land, construction financing interest, cost of selling or renting the created units, legal fees, and other nonbrick-and-mortar items. In this case, it turns out that the price of materials is only one-third the total development cost. However, the choice and use of materials may also affect the speed of construction or the appeal to consumers, and this in turn affects the total price. For example, a 25% saving in overall construction time (a not-uncommon occurrence with the advent of new building technology) could save $170,000 in construction interest at 9% on a 10 million dollar project with a conventional 1.5-year cycle time.

When a purchaser buys a house, apartment, or pays rent, the price of occupancy becomes an additional factor. Each year, there are the maintenance and operating costs and the cost of interest for permanent financing, with the exact amount depending upon interest rates, type of construction, fiscal needs of a community, and management practices. While materials per se are a small component of the total occupancy cost, the effect of materials technology can be quite significant. Thus, a relatively small outlay for a better appliance or material can lower maintenance and operating costs appreciably and increase value. As long as this added outlay does not substantially restrict the market—i.e., price a significant number of families out of housing—the value-added may be marketable. As a corollary, modernization of buildings is also a substantial activity affecting personal, business, and national economies.

Materials Research and Development Emphasis: Information from building-product manufacturers reveals that the majority of their research and development effort is directed, not towards developing or exploiting new materials, but toward adapting the materials in which they have an established interest (i.e., a mining and/or manufacturing position) in order to lower installed costs, to reduce operating and maintenance costs, to combine function, to find new applications, or to provide comfort and safety. To reduce installed costs, such development programs seek to produce simplified methods of fastening, decrease product complexity, increase compatibility with interdependent subsystems, reduce number of parts needed for field assembly, and decrease material-handling and transportation costs. In these developments, individual materials, regardless of the principal reason for their selection in a given instance, tend to be viewed in the context of total system performance. In the area of operating and maintenance costs, long-term owners are recognizing that costs over the term of proprietorship can decrease significantly if initial design-and-build decisions take into account time-dependent costs. Technology is increasingly expected to help reduce operating, replacement, and maintenance costs as well as first costs—a concept that is coming to be known as "life cycle costing."

Energy shortages are a factor increasingly affecting materials selection. Opportunities for conserving energy exist by controlling a host of variables, including window size, lighting levels, amount of outside air recirculated, design and operational characteristics of electrical equipment, utilization of insulation, and building orientation and geometry. Definitive quantitative analyses of the significance of all of these variables under a variety of conditions are still at an early stage of applicability.

Fire safety and resistance to natural hazards and noise are being recognized as important areas for materials development. Fire-safety design is predicted in large measure upon contents of buildings, more popularly referred to as building "fire load." Until recently, fire load data (as reported by the National Bureau of Standards) were based upon studies during the 1920's and 1930's; updating of such data merits high priority. Fire-safety practices include compartmentation; providing places of refuge; smoke-removal devices; smoke and heat detectors; communication systems; sprinklers, safety-exit planning; and elevator-emergency service. The development of needed criteria for fire-resistant construction materials requires acceleration to complement these practices.

The foregoing discussion of cost factors in housing suggests that materials R&D will have little influence on the construction industry from the standpoint of materials costs. Thus, in the case of private homes, it is estimated that, on an average, the cost of the building is 33% of the purchase cost; land, 25%; and financing, 42%. Less than 50% of the cost of the building goes into the cost of materials; as a result, a 10% savings in materials amounts to less than 2% of the total cost of a home. Even industrialized housing, if it were technically practicable, is likely to do no more than keep building costs steady with present practices. Nevertheless, despite the small impact of direct materials costs, significant cost reductions could arise from increased efficiency in the processes by which materials are incorporated in the buildings, e.g., savings in the 42% labor costs associated with this step.

Another important factor that will influence materials R&D for the industry in the future is the performance approach, as developed in particular by the Building Research Advisory Board of the National Research Council. The performance concept—involving criteria and specifications to meet them— has spawned a growing use of value engineering or consideration of alternatives during the design and procurement stages. This development increases the effectiveness of the competitive process over the traditional bidding among contractors against a fixed design material, or product specification. Most critically for materials, the role of the building-product producer is increased significantly in optimizing the structure through flexibility in materials performance and adaption to desirable processing modes.

Finally, the issue of constraints peculiar to the building industry has significance for the role to be played by materials. The Committee on Urban Technology of the National Research Council, in its report on "Long Range

Planning for Urban Research and Development," has pointed out that "a rewarding field in which to seek cost reduction lies in the identification and reduction of constraints imposed by tradition and present practice."

A detailed analysis of such problems by the Building Research Advisory Board identified the availability of materials as one of the constraints needing attention. While, the present study has reached a different conclusion regarding availability per se, it is clear that major constraints do exist due to high materials cost, performance limitations, and the ways in which materials are processed into construction products, components, subsystems and total systems. A key factor affecting materials in this respect is the currently limited viewpoint and policies of building-product manufacturers, particularly those with already established commitments to specific materials. Likewise constraining is the time required to develop an innovation to practice—on the order of five years. Hence, the cyclical character of the building industry and its sensitivity to many external influences tends to retard the exploitation of innovations. In another area, the movement toward doing more assembly work in the factory rather than onsite has introduced new factors, namely those associated with fixed costs of manufacturing. Consequently, increased automation and factory fabrication seem to have been occurring only in cases of intensive repetitive building where there is confidence in a continuing market large enough to permit amortizing the plant investment involved. It is clear that the fragmented character of the building industry is a severe obstacle in the extent to which major advances from materials performance and processing efficiency can be expected to be utilized.

Materials and Standards

Before a new material can be efficiently used in manufacturing and commerce, the properties and performance of the material must be described and specified. Both the functional value and the characteristics must be standardized if the new material is to be obtained competitively, and priced appropriately. The description of the desired characteristics of the material takes the form of a "standard specification," which expresses the material characteristics in terms of quality, uniformity, and performance, in order to measure its ability to fulfill specific application requirements. For example, when a ton of structural steel is purchased for a specific price, the latter is related directly to a particular specification which stipulates the chemical composition (allowable limits on the amount of carbon, manganese, phosphorus, sulfur, silicon, and copper), the minimum allowable strength and ductility, etc. Thus, this standard specification defines the quality and therefore the value of the steel. In turn, to measure whether the steel meets these stipulations requires standard methods of test.

Standards defined in this way are useful in every step of the manufacturing cycle—design, materials, processes, and product. Accordingly:

- Standards define the performance properties required by the user.

- The designer adopts standards to determine the capabilities and limitations of the material involved.
- The manufacturer uses standard purchasing specifications in order to define what he wants, and standard methods of test to insure that the material he receives meets the specifications.
- The materials producer employs the standard specification to design his manufacturing processes and he also uses standard methods of test for production quality control.

Given that standards have wide utility, how are they generated and accepted? In the U.S., the mechanisms are several. In the first place, guidelines are provided by the selectivity of the consumer that sets requirements in terms of saleability, and by the public responsibilities of state and federal governments in establishing requirements for health and safety. In industry, materials producers and their trade associations write standards to define the quality of the materials they produce, while manufacturers and builders write standards to define the quality of the materials they wish to buy. Moreover, agencies of government, such as the General Service Administration, the Department of Defense, and state purchasing authorities set standards to define the quality of materials used in items purchased for public purposes. Sometimes these specifications are combined into national standards. The National Bureau of Standards plays an extensive role in the latter area through development of measuring and testing techniques, and standard reference materials. The existence of nationally accepted and recognized materials standards provides the engineering designer with a basis for materials purchases without proprietary sourcing and with reasonable assurance of continued quality and performance. Generally, standards are reviewed and updated continually to meet changing requirements and technological improvement.

Three types of standards are in general use in the U.S.

(a) Mandatory standards, such as those set by the government in the areas of health and safety.
(b) Voluntary standards, such as those generated by trade associations and technical societies.
(c) Voluntary consensus standards, which are developed by groups in which the producers, the consumers, and other interests agree on quality and availability.

Voluntary standards are developed by such trade associations as the Electronic Industries Association, Aerospace Industries Association, and the National Electrical Manufacturers Association. In the evolution of such standards, input from interested parties outside the industry is often limited. In the same class of voluntary standards, a somewhat greater input from outside the industry can be achieved by certain professional and technical societies, such as the Institute of Electrical and Electronic Engineers, the Society of Automotive Engineers, and the American Society of Mechanical Engineers.

Voluntary consensus standards in the materials area are developed by the American Society for Testing and Materials. The standards writing committees include representatives from all interested producers and consumers as well as from governmental agencies, consultants, academic and research institutions; in short, everyone who has an interest in the development of a standard and who is technically qualified is eligible for membership. The annually published compilation of standards available through this mechanism includes standards for materials in many other countries in addition to the U.S.

The American National Standards Institute is chartered to act as coordinator and clearinghouse for voluntary standardization within the U.S. It was organized, not to develop standards, but to assign national status to standards adopted by the trade associations, technical societies, and other member organizations working on voluntary standards. It also serves as the focal point for U.S. participation in international nontreaty standardization activities.

Certain large corporations also generate written specifications. These include AT&T, General Motors, General Electric, and Standard Oil. Large retailers and merchandisers such as Sears or Wards also develop their own specifications and testing requirements. In other corporations, qualifications for materials typically derive from functional trial and use.

MATERIALS IN GOVERNMENT

Introduction

The materials research and development program of the federal government has played a major role over the past two decades in shaping the whole field of MSE as it is today—its institutions, scope, research activities, and educational endeavors. The federal program has evolved from modest beginnings after World War II to its present significant scale of activity, corresponding to a total level of funding of more than a quarter of a billion dollars of direct federal support. Such growth is associated largely with responses to legislative recognition, as matters of public policy, of the changing character and scale of national needs and goals. The current magnitude and distribution among federal agencies of direct funding for materials R&D is summarized in Table 7.27, which demonstrates both the range of agencies involved and the relative emphasis of effort. Table 2.14* shows the distributing agency emphasis on classes of material.

The forces and motivations that influenced the major directions of the federal materials program over this period have included political, economic, and technical concerns. In the years immediately following the end of World War II, during the period of the "cold war," the need was recognized for an increased effort in defense-related materials, both conventional and nuclear. Thus, the major national laboratories of the Atomic Energy Commission (AEC) were established during this period, and there was a large buildup in the electronics industry of materials research in support of Defense Department (DoD) interests. In 1954, the Atoms for Peace program launched by President Eisenhower led to the AEC charter being amended and broadened, with the agency being charged with the responsibility of furthering the "development of nuclear energy for peaceful purposes" —such as civilian power plants and isotope utilization in industry—and of generally insuring that the nation stayed in the lead in nuclear science and technology. These developments had the direct effect of enlarging the scope of the AEC materials R&D programs, particularly in basic research.

The dramatic and successful flight of the first earth-orbiting satellite in October 1957 by the Soviet Union sharply influenced U.S. government activities in scientific research and related education. The corresponding emergence in the late fifties of "conquest of space" as a new U.S. national goal resulted in a new agency, the National Aeronautics and Space Administration (NASA). In a few years after Sputnik, the federal budget for materials R&D nearly doubled. The concept of an interdisciplinary approach to materials research, which had been slowly developing, was given a strong stimulation through the establishment of a multi-million dollar program of Interdisciplinary Materials Research Laboratories (IDL's) at a number of universities by the Advanced Research Projects Agency (ARPA) of DoD, together with analogous efforts by the AEC and, on a more modest scale, by the NASA. These efforts, which are discussed in more detail in the subsequent section on University Education and Research, were directed to expanding the materials research effort in the universities and, correspondingly, its output of Ph.D.'s specializing in materials. Increasing the quality of materials research and

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* Chapter 2, Volume I, of this Series.

TABLE 7.27 Direct Federal Funding of Materials Research and Development by Agency (Fiscal Year 1971)

Agency or Department	Funding Level Millions of Dollars	Percent Total
Agriculture (USDA)	22.6	8.7
Atomic Energy (AEC)	82.2	31.6
Commerce—National Bureau of Standards	10.5	4.0
Defense (DoD)	100.4	38.6
Health, Education and Welfare (HEW)	3.6	1.4
Interior (USDI)	3.5	1.3
National Aeronautics and Space Administration (NASA)	22.6	8.7
National Science Foundation (NSF)	10.6	4.1
Transportation (DoT)	4.2	1.6
TOTAL	260	100

education through improved instrumentation and facilities, and promotion of interdisciplinary cooperation were also major objectives. With the development of these various federally-supported materials research facilities at universities, the concept of a mission-oriented agency supporting basic research not necessarily related to its direct interests was established. This concept was not to be questioned until the late 1960's.

Now, in the 1970's, the forces and national needs which influenced the program in the sixties are still valid, although with dimished urgency. Some new concerns have made their debut in the last few years—concerns that are oriented toward society's more immediate interests, such as pollution control, health care, improved transportation, housing, etc. Some of the effects of these new pressures are already evident: the AEC charter was amended in 1968 to permit it to participate in environmental studies; expenditures on space have been drastically reduced; and the ARPA IDL's have been transferred from DoD to the National Science Foundation (NSF). The full import of these changes, however, is yet to be seen.

Before discussing the details of federal materials funding and the relevant activities of the principal agencies, it is appropriate to review briefly the role of agency interaction and coordination. For materials R&D, this role has had several singular features which illustrate the recognition accorded to materials in the overall federal program. Within a relatively short period after the creation by President Eisenhower in November 1957 of the Office of Special Assistant to the President for Science and Technology, the need for an effective mechanism to coordinate such federal agency activities led to the formation of the Federal Council for Science and Technology (FCST), and the earliest committee of the FCST, created in the first month of its existence (March 1959), was the Coordinating Committee on Materials Research and Development (CCMRD). The initial activity of CCMRD was the recommendation, based on considerable earlier discussion, that eventually led to the establishment of the Interdisciplinary Materials Laboratories mentioned above. Subsequently, the Committee proved an effective mechanism for information exchange and cooperative interagency analyses of materials areas of common concern. Such studies were directed to major materials barriers standing in the way of necessary technological progress (the Road Blocks Study), character and costs to the nation of materials degradation by corrosion, opportunities in biomaterials research, etc.

Over the first decade of the FCST, as the strength of federal R&D programs expanded within the individual agencies, the pressures of such activities tended to weaken the interest of the agencies in coordination and joint efforts through the FCST. The increasing difficulty experienced by CCMRD in getting responsive FCST or agency action to the recommendations in its reports is an illustration of this trend (see, for example, the testimony by W.O.Baker, Hearings of the Committee on Science and Astronautics, U.S. House of Representatives, 19 July 1973). In July 1969, as an outcome of these difficulties, the then President's Special Assistant for Science and Technology, also the Chairman of the FCST, dissolved the CCMRD along with several other committees.

In December of the same year, the Chairman initiated the Interagency Committee on Materials (ICM) as a "novel element" of the FCST in that it was partly sponsored in collaboration with the National Research Council (NRC) of the National Academy of Sciences, i.e. outside the federal agency system. The newly reconstituted National Materials Advisory Board (NMAB) of the NRC was designated as the formal liaison to the ICM—the membership of which remained solely officials of the federal agencies having materials R&D activities or interests. The ICM reestablished the coordination and interaction efforts of its predecessor, and expanded membership or observer status to a wider range of agencies (including all those in Table 7.27), in recognition of a broadening of national issues in which materials are significant—for example, health and housing. Despite certain advantages in the new arrangement, the difficulties of implementation encountered in the earlier era do not appear to have been overcome. Following the Federal Reorganization of 1973, including the President's designation of the Director of the National Science Foundation as the Science Adviser to the President in July 1973, the new Chairman of FCST has indicated a concern for the improvement of the strength and effectiveness of the Council and, specifically, the interagency activities in materials.

Structure and Funding

In pursuing national goals, the government has financed the development of a substantial capability for R&D in materials. The rate of funding for this capability grew to significant proportions in the decade following World War II, and then increased by almost a factor of ten in the six to eight years following Sputnik. This capability consists of a large number of university programs with the capacity to train students in research, extensive research staffs in governmental laboratories, federal contract research centers, and federally-supported activities or facilities in industrial laboratories.

Funding

The direct federal support of materials R&D is shown in Figure 2.8* in actual dollars and 1964 dollars[7], over the period 1962 to 1971. It is seen that the support in current dollars increased some 40% over that period— from $0.18 billion in 1962 to $0.26 billion in 1971. However, the number of people who can be supported in a given year (as a direct measure of actual effort) is proportional to the value of that year's appropriation in 1964 dollars. Thus, the number of workers supported by the government peaked in FY 1966, and from FY 1966 to FY 1971 dropped about 15%. This closely follows the pattern for all federal R&D funding in that period.[8] The effective decline in governmental support, coupled with the record production of new

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* Chapter 2, Volume I of this series.

[7] These and the following figures are from Interagency Council for Materials (ICM) Funding Survey of Federal Directly Supported Materials R&D, August 1971.

[8] National Patterns of R&D Resources, 1953-1970. National Science Foundation, NSF-70-46, p. 2.

graduates, became one of the main reasons for the tightness of the job market.

The federal expenditure for materials R&D in FY 1971 was some $0.26 billion. Various classifications of interest within this total are:

Where spent:

In-house governmental laboratories	32%
Federal contract research centers	23%
Universities	20%
Industry	20%

Spent on:

Applied research	54%	Metallic Materials	37%
Basic research	38%	Organic materials	21%
Experimental development	8%	Inorganic nonmetallic materials	24%
		Composite	10%
		Others	8%

Supported by:

DoD*	38% (30%)**
AEC	31%
NASA	8%
Department of Agriculture	12%
NSF	4% (12%)
NBS	4%

Major supporters of applied research ($0.14 billion):

DoD	40%
AEC	30%
NASA	10%
Department of Agriculture	9%
NBS	6%

Major supporters of basic research ($0.097 billion):

AEC	40%
DoD	32% (18%)**
Department of Agriculture	10%
NSF	9% (23%)
NASA	5%

Distribution of applied and experimental development expenditures ($0.12 billion) with respect to national missions or goals:

Defense	42%

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* DoD = Army, Navy, Air Force, and ARPA.

** Numbers in parentheses reflect shift if ARPA funds are included with NSF.

Nuclear energy	26%
Space technology	11%
Transportation	1%
Agriculture	7%
Standards (NBS)	5%

The above breakdowns are for FY 1971, but they are also valid for FY 1966–70 within a few percentage points, which indicates a negligible shift in the relative effort of the different agencies or the general types of materials studied. Therefore, any changes in national priorities since 1965 have not resulted in a significant amount of new funding, or shifts from one agency to another.

Governmental Laboratories

The word “material” has many different connotations, and MSE represents disciplines that are very broad in scope. Likewise, advances made in MSE contribute widely to the betterment of almost all aspects of human life, including health, safety, and economic well-being. Thus, it is understandable that there is a whole multitude of areas within the definition of MSE where various governmental agencies either have a primary responsibility, or at least play an important role in conducting basic and applied research on materials, and in the experimental development of new and improved materials.

For example, the Department of the Interior has the prime responsibility for materials research involving the extraction and processing of minerals, ores, and fuels, and the Atomic Energy Commission is primarily responsible for research involving fissile materials and their utilization in such applications as power generation and nuclear medicine.

Because of this great diversity of materials activities within governmental laboratories, it is difficult to generalize as to any fundamental or unique policy, program, or role of these laboratories. However, in examining the many mission statements and programs of the various laboratories, it seems clear that the underlying role of the vast majority, if not all, of the governmental materials research laboratories is that they are essentially problem solvers. That is, the laboratories are devoted to obtaining solutions, within a short period of time, to specific materials problems that for the most part are intimately related to an overall agency or department mission. This might be contrasted with the role of university activities, including the MRL’s which historically have been more heavily involved in basic materials research, the primary objective of which is to gain new knowledge and understanding, and which may have very little practical application, at least over the shorter term.

Although governmental materials research laboratories tend to emphasize applied research and exploratory development of new and improved materials, most seem to perform a reasonable amount of basic research in areas relevant to their missions in order to maintain or increase the necessary ability of their staffs to provide a viable base in support of their problem-solving responsibilities. The percentage of basic or exploratory research varies considerably from laboratory to laboratory, but a reasonable norm for the larger research laboratories seems to be in the range of 5–15% of total funding.

Another important point is that in carrying out its missions, it is not unusual for a government-sponsored laboratory to become the leading national center of excellence in certain specific areas. For example, the Air Force Materials Laboratory (Wright-Patterson, Ohio) has become the national leader in composite materials research, the Atomic Energy Commission's Holifield National Laboratory is a national center of excellence in research on fissile materials, and the National Bureau of Standards has a well-recognized national center for research on polymeric materials. Hence, even though the governmental laboratories might emphasize applied R&D, they tend to have excellent fundamental research capabilities in many areas.

The following list offers a representative sample of the hundreds of government-operated R&D installations, many of which have some materials research activities. The missions of the parent agency or department is also given to help tie the mission of the laboratory to overall agency objectives.[9]

Department of Agriculture: The Department is directed by law to acquire and diffuse useful information on agricultural subjects in the most general and comprehensive sense. The Department performs functions relating to research, education, conservation, marketing, regulatory work, agricultural adjustment, surplus disposal, and rural development.

Forest Service. The Forest Service of the U.S. Department of Agriculture is charged with the responsibility for promoting the conservation and best use of the nation's forest lands, amounting to approximately a third of the total land area of the U.S. The Forest Service carries on a balanced research program to help solve the forestry problems confronting the nation. An example of a materials research laboratory in this area is the Forestry Sciences Laboratory in Athens, Georgia.

Forestry Science Laboratory. Mission: Study characteristics of southern species and their relationship to product classification and ultimate utilization; develop means of achieving more efficient use of wood in housing and construction, with emphasis on southern species.

Description of current important programs: Develop grading systems for predicting veneer yields by grade from four major species of southern pine and investigate effects of environmental factors on specific gravity of wood. Investigate environmental factors affecting wood in housing and construction, evaluate effectiveness of on-site preservative treatments, and develop new and improved wood products, systems, and designs to more efficiently utilize wood in light-frame and other construction. Conduct research on microscopic and macroscopic characteristics of wood, environmental influences, and effect on wood quality and end-use. Develop systems designs and improved methods for more efficient use of wood in light-frame and other construction, and investigate more effective processes for controlling effects of environment on wood used in construction.

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[9] A general listing of government laboratories is given in Directory of Federal R&D Installations (National Science Foundation Pub. NSF 70–23) and Department of Defense In-House RDT&E Activities (DoD Management Analysis Report 70–4).

Atomic Energy Commission: The purpose of the Atomic Energy Act is to provide by, national policy, that the development, use, and control of atomic energy shall be directed to make the maximum contribution to the general welfare and to the common defense and security, and to promote world peace, increase the standard of living, and strengthen free competition in private enterprise. The Atomic Energy Commission provides and administers programs and encourages private participation in such programs for research and development, international cooperation, production of atomic energy and special nuclear materials, and the dissemination of scientific and technical information. The Commission has the responsibility to protect the health and safety of the public, and to regulate the control and use of source, byproduct, and special nuclear materials.

Sandia Laboratories. Mission: To conduct the materials R&D necessary to support stockpile management, specific development of weapons, and exploratory research and development essential to existing and future weapon needs.

Description of current important programs: The range of programs spans the conventional materials efforts in metallurgy, plastics, ceramics, ferro-electrics, thermoelectrics, and explosives, as well as composite materials. Included in this broad range is the investigation of materials behavior in extreme environments, such as radiation effects on high temperatures. In addition to the mission statement, many peripheral efforts exist which reinforce the materials R&D, e.g., dynamic properties of materials, underground testing, and simulation capabilities.

Argonne National Laboratory. Mission: Applied and basic aspects of nuclear research. Applied areas concentrate on development of liquid-metal fast-breeder reactors whose eventual commercial development will be for generation of electricity. Basic research is largely nuclear-related in areas of applied mathematics, biology and medicine, chemistry, high-energy physics, metallurgy, nuclear physics, and solid-state science.

Description of current important programs: Reactor-related programs include sodium corrosion, fuel-element performance, radiation-induced swelling and plasticity. Basic studies aim to increase understanding of materials, especially in areas of direct interest to the AEC. Areas of study include neutron scattering, radiation effects, superconductivity, mechanical properties, and the study of actinide compounds.

Department of Commerce: The mission of the Department of Commerce is to promote full development of the economic resources of the U.S. It does this through programs and actions that encourage and assist states, regions, communities, industries, and firms towards economic progress. Specific programs carried out include the collection, analysis, and dissemination of demographic, economic, business, scientific, and environmental information; the promotion of exports and increased travel to the U.S., and the provision of financial and technical assistance to regions and communities with lagging economies.

National Bureau of Standards. The National Bureau of Standards (NBS) is a principal focal point in the federal government for assuring maximum application of the physical and engineering sciences to the advancement of technology in industry and commerce. To this end, NBS conducts research and provides central national services in four broad program areas. These are (a) basic measurements and standards, (b) materials measurements and standards, (c) technological measurements and standards, and (d) transfer of technology. The Institute for Materials Research is a principal focus for NBS materials work. Its mission includes: furnishing certified Standard Reference Materials for the calibration of measuring instruments, and test methods, quality control, and research; developing new and improved methods for measuring the properties of materials; generating and evaluating scientific and engineering data on well-characterized materials; relating the physical and chemical properties of materials to their behavior and their interaction with their environments; providing advisory, consulting, research, and technical services to other governmental agencies in support of their statutory responsibilities.

Department of Defense: The Department of Defense was created as a part of a comprehensive program designed to provide for the future security of the U.S. through the establishment of integrated procedures for the departments, agencies, and functions of the government relating to the national security.

Advanced Research Projects Agency. The Advanced Research Projects Agency (ARPA) is a separately organized research and development agency of the Department of Defense under the direction and supervision of the Director of Defense Research and Engineering. It is responsible for basic and applied research and development for such advanced projects as the Director of Defense Research and Engineering assigns. The Agency utilizes the services of the military departments, other governmental agencies, private, industrial, and public entities, individuals, and educational or research institutions to perform its projects.

Department of the Army. Electronic Research and Development Laboratories; Electronic Components Department; Electronic Parts and Materials Division; Fort Monmouth, New Jersey.

Mission: The Electronic Components Department is responsible for that part of the USAELRD mission devoted to development of materials, electronic and nonelectronic components, and component assemblies. This responsibility encompasses applied R&D on materials, electron tube and solid-state devices, frequency-control and selective devices, and power sources; and also in the general category of electronic and nonelectric components, component modules, specialized packaging of component assemblies, close cooperation with the Institute of Exploratory Research, and accomplishment of such exploratory research tasks that may be assigned.

Description of current important programs: Provision of new electronic materials such as magnetic, dielectric, ferroelectric, insulating, and conducting materials to achieve new electronic parts or multifunctional circuit devices, such as low-frequency circulators, phase shifters, antenna arrays, piezoelectric elements, capacitors, etc.

Department of the Navy. Naval Research Laboratory, Washington, D.C.

Mission: To conduct a broad program of scientific research and development in the physical sciences and related fields directed toward new and improved materials, equipment, techniques, and systems for the Navy.

Description of current important programs: Surface chemistry, lubricants, fuels, polymers, elastomeric materials, coatings, composites, fire-extinguishment and control, dielectrics, corrosion, radiation damage, physical metallurgy (fracture mechanics, fatigue, metal physics, welding fundamentals, refractory metals).

Department of the Air Force. Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

Mission: To plan, formulate, present, and execute the AFSC exploratory and advanced development programs in the areas of materials sciences, metals and ceramics, nonmetallic materials, materials composites, materials analysis, manufacturing technology, and materials applications; to conduct in-house research to maintain a high level of technical competence; to act as AFSC focal point for information in the assigned technical areas; to execute assigned projects for and closely with the Army, Navy, NASA, ARPA, AEC, and other governmental agencies; to support other AFSC programs and insure the rapid application of research and technology to advanced systems.

Description of current important programs: Materials and techniques for A/C structural integrity and reliability. Materials and techniques for AF weapons survivability and hardening. Tactical and limited warfare materials and technology support. Manufacturing technology of new materials for systems applications. Advanced composites, metals and alloys for airframe and propulsion structure.

Department of the Interior: In formulating and administering programs for the management, conservation, and development of natural resources, the Department pursues the following objectives: assurance of adequate resource development in order to meet the requirements of national security and an expanding national economy; the maintenance of production capacity for future generations; the promotion of equitable distribution of benefits from nationally owned resources; the discouragement of wasteful exploitation; the maximum use of recreational areas; and the orderly incorporation into our national life by creating conditions which will advance their social and economic adjustment.

U.S. Bureau of Mines. Albany Metallurgy Research Center.

Mission: To conduct fundamental and applied studies on long-range problems which are not commercially attractive to private industry, and short-term problems important to maintaining an adequate and sufficient supply of mineral materials at the lowest cost consistent with maintaining the national security, healthful working conditions, and preservation of the environment.

Description of current important programs: R&D programs are conducted in benefication and metallurgy to assure adequate supplies of mineral materials and to develop ways and means of utilizing or economically recycling mineral wastes. Program elements are centered about extractive metallurgy, chemical processing, materials science, metals processing, and thermodynamics.

National Aeronautics and Space Administration: In carrying out the policy of Congress that activities in space should be devoted to peaceful purposes for the benefit of all mankind, the principal statutory functions of NASA are: (1) to conduct research for the solution of problems of flight within and outside the earth's atmosphere, and develop, construct, test, and operate aeronautical and space vehicles; (2) to conduct activities required for the exploration of space with manned and unmanned vehicles; (3) to arrange for the most effective utilization of the scientific and engineering resources of the U.S. with other nations engaged in aeronautical and space activities for peaceful purposes; (4) to provide for the widest practicable and appropriate dissemination of information concerning NASA's activities and their results.

NASA—Ames Research Center. Chemical Research Projects Office.

Mission: To identify the chemical and materials research and technology required for solutions to problems related to the aeronautics and space efforts of the Agency and other problems of national concern which could be solved by the application of space material technology. To conduct both basic and applied interdisciplinary R&D on chemical problems, mainly in areas of macromolecular science and fire research in order to solve these problems. To provide liaison with engineering community and effective transfer of research achievements and technology to other agencies and industry.

Lewis Research Center. There are several major objectives embodied in the materials science and engineering programs at NASA-LeRC. These are (1) to extend the capability of materials and processing technology so that advanced materials can be effectively exploited, particularly in aerospace, but also in some nonaerospace applications; (2) to obtain a better understanding of the failure and fracture mechanisms involved in the application of advanced materials to aerospace structures and propulsion systems; and (3) to develop methods for predicting in advance of service the life of aerospace structural components subjected to complex patterns of temperatures and loads as a function of time.

To achieve these objectives, research is under way to improve the capability of a number of alloy systems, including titanium, iron, nickel, cobalt, and chromium-base alloys, as well as refractory compounds which have potential for ultrahigh-temperature applications. Approaches being taken include alloying, dispersion strengthening, prealloyed-powder technology, thermomechanical processing, and directional solidification. Specific areas of corrosion associated with aeronautics applications, such as hot-salt stress corrosion of titanium alloys and oxidation and sulfidation of superalloys, are under investigation. Similarly liquid-metal corrosion, which is pertinent to space power applications, is under investigation. The development of advanced fiber and laminate composite materials (both polymer matrix and metal matrix) with superior properties is oriented toward the use of these materials in gas turbine engines and space-oriented applications such as the Space Shuttle.

To extend existing life-prediction techniques, research is under way to develop new methods for determining stress and strain distributions in the vicinity of flaws or cracks. Various approaches are being examined for predicting the time to initiation of the first detectable crack as a result of mechanical and thermal fatigue and to predict the propagation rate of these cracks. Standard fracture-test methods are being developed to properly characterize the fracture behavior of materials.

Of course, implicit in each research area are basic studies designed to contribute to the understanding of fundamental material behavior.

National Science Foundation: The fundamental purpose of the National Science Foundation is to strengthen research and education in the sciences in the U.S. Among the activities of the Foundation are the awarding of grants and contracts, primarily to universities and other nonprofit institutions, in support of scientific research. These include the support of many laboratories engaged in various aspects of materials research. (See later discussion of NSF activities.)

Federally Supported R&D in Universities and Industry

The primary characteristic of American science support is that it is pluralistic and diffuse. There is only one agency (NSF) with an overall mandate to support science and technology generally; all the others, with the lion's share of the budget, support an agency mission. The picture is thus inherently complex, and any attempt to evaluate it fairly would have to ask detailed questions not only about the health of the extramural materials apparatus, but also about how well the various agencies have been served by the science and technology thus generated. COSMAT was not structured to carry out such an assignment in detail, so we shall restrict attention to a few generalizations, and make a few rough estimates about how the machinery has worked in the past and how it may be expected to respond to the new future challenges.

Research-Mission Coupling Structure: The working structures of the various agencies spread over a considerable spectrum as outlined below, depending upon how closely coupled the research output is to the agency mission, and what type of office does the funding.

Research Funded Under a System Contract. Some applied materials research (primarily industrial) is carried out under the terms of the prime contract for the development of a particular system. For example, a substantial amount of materials work in the DoD is performed as an integral part of missile nose-cone development, and is carried out in the various industrial laboratories charged with the development of that system.

Governmental Laboratory Extramural Programs. Some governmental laboratories have extramural budgets for work in direct support of the laboratory programs. These activities are conceived as actual extensions of in-house laboratory projects, and have multiplying effects on the technical staff. In the hands of groups like the Air Force Materials Laboratory management, such arrangements serve important functions. For example, it is through such support formats that the Air Force oversees such industrial developments as its titanium program and its composite-materials development program.

Mission-Related Research Offices. A further point on the scale corresponds to offices whose sole function is the funding of mission-related research. A subcategory contains offices which fund both in-house and extramural research. The AEC and NASA afford such examples, since each has an office which is responsible for the entire in-house and extramural agency budget in materials. In such cases, research strategy-making is centralized, and the extramural activities are subject to considerable feedback from the in-house laboratory people. ONR is also, at least partially, an example of this type of office, since NRL is also funded through ONR, although there is at least partial separation from the extramural program, in that different sections of ONR are responsible for NRL and for the extramural programs.

The second subcategory pertains to offices whose sole or primary purpose is extramural research. The dividing line is of course not sharp, because offices such as ARPA actually sponsor in-house DoD and other governmental work on a selective basis, and in most cases use monitors from other Defense Department offices such as the Army Research Office to monitor the extramural research contracts.

In all cases of offices which carry on extramural research in support of an agency mission, much attention is given to feedback mechanisms whereby the agency in-house laboratory and project personnel interact with (and on) the extramural program. An excellent analysis of this interaction has recently been carried out in a series of case studies for certain early ONR operations.[10] As detailed in the study, ONR early developed liaison with the related technical branches of the Navy, e.g., the Bureau of Aeronautics and the Bureau of Ordnance, etc., and its program goals and strategies were tailored with the technical needs of these offices as well as the overall Navy in mind. These interactions and concerns are features of each of the offices of this type.

National Science Foundation. The final point in the spectrum is occupied by NSF, which traditionally has focused primarily on the needs of the university science community rather than on specific technical output in terms of a particular mission. Some striking changes have very recently occurred in the mandate and goals of the NSF, but it is too early to tell what impact these will have in the long run. In recent years, NSF has been forced to act excessively as a flywheel to the rest of the supporting agencies; in a number of instances, important projects have been terminated within the mission agencies, and NSF has absorbed them. In the materials area, the ARPA Interdisciplinary Laboratories and the National Magnet Laboratory are examples.

The previous paragraphs illustrate the extreme variability in the agency structure of groups currently supporting materials research in this country. Since the support structure is mainly mission-based, a variety of formal and ad hoc committees and groups have grown up to coordinate the whole picture. These committees usually have little policy responsibility, but they do serve a number of information-sharing functions, and they sometimes carry out studies and make important recommendations on general policy on materials matters to the Federal Council, the Office of Science and Technology, as well as within the various agencies. The information-sharing is by no means a trivial activity because by means of it the university small-scale principal-investigator activities are coordinated, and a finely-tuned balance can, in principle, be achieved on desirable levels of support for individual groups. Another important result is that when a desirable activity is phased out of one agency for internal reasons, the system usually responds elsewhere (as mentioned above in connection with the NSF).

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[10] Case Studies of ONR-Supported Research, E.Salkowitz, R.Armstrong and J. Haim, IDA Paper, p. 645 (1970).

Research-Support Styles

Orthogonal to the research-coupling axis discussed above, another spectrum can be plotted consisting of support styles and formats. These styles again reflect a rich variation depending upon the particular goal. Several themes can be discerned:

Special Arrangements to Effect a Unique Result: Solicited Proposals from Selected Vendors. This is the method of choice when an agency is faced with a special short-term problem and there is a small potential group of contributors. It is not a popular format, except for highly applied projects.

Special-Purpose Laboratories: Examples: The National Magnet Laboratory (MIT) for the study of material properties at high-magnetic fields is a facility available nationwide to research people on petition. The AEC National Laboratories furnish unique facilities for neutron research, etc., and are also available widely to the research community. The Ames Laboratory is supported by AEC for the specialized study of rare earths. The Materials Laboratory at Pennsylvania State University specializes in new materials and crystal growth.

"Named" Programs: The purpose in this case is normally to stimulate new activity in a relatively narrow field of special importance.

NSF Science Development Program. The purpose of this presently terminating program is to create new excellence at the second-tier universities. There are no special requirements in terms of fields to be pursued; rather, excellence is sought on its own grounds.

ARPA Coupling Programs. These are industry-university cooperative programs aimed at fields of special importance.

AROD Military Themes. Unsolicited proposals on "ONR format" (see below), but aimed at specific fields deemed of special Army significance.

NSF Science Fellowships, Traineeships, etc.

Directed Short-Term Research (often system-related): Under programs with a definite timetable and specified product, short-term research programs are often funded to resolve some aspect of the project. The titanium research projects supported under the Air Force titanium development program are examples. A number of ARPA programs such as that on nondestructive testing are also examples.

Individual Investigator on ONR Format: In this familiar technique, unsolicited proposals are received over a wide, but mission-biased, field. Those proposals within the mission of the office are then judged on their scientific merit, often by outside panels of experts. Since this format has the effect of rewarding only the best ideas on an open nationally competitive basis, it has traditionally been the most effective way to stimulate creative performance at the frontiers by the academic science establishment. It has proved especially effective in universities already operating under some kind of umbrella institutional funding, and is not seen as an alternative to, or in competition with, such institutional funding. The impact on the agency mission is in varying degrees long-term and indirect. Scientific matters aside, clearly an effect of great value is the investment the agency is able to make in assuring itself of a cadre of technically trained people with expertise in relevant technical areas. The Defense Department without its aerospace engineering talent in the defense industry would clearly be in deep trouble. Indeed, now after 25 years of university research support, the manpower implications of what the federal government does have become drastically apparent.

The Interdisciplinary Laboratories: The IDL format is a significant one in the field of materials. Inasmuch as a separate and more detailed evaluation is given in the following university section, it will be described only briefly here. The history of the initiation of the IDL began in the Sputnik era when the nation was rapidly expanding its science base. A number of factors which made the field of materials particularly ripe for takeoff included: (a) recognition of the generality of materials requirements in each of the high-technology agencies—DoD, NASA, and AEC; (b) realization that a synthesis was required in the field itself between its subelements of solid-state physics, metallurgy, chemistry, and electrical engineering; (c) the need for augmentation of the individual investigator format. (In the late 1950's, for example, the individual investigator system required new capitalization in the form of additional laboratory space and major facilities unavailable under that format.)

The program was spawned in three agencies—ARPA, AEC, and NASA—with slight variations in each, through the new Coordinating Committee for Materials Research and Development (CCMRD) set up as an arm of the Federal Council of Science and Technology. Currently the ARPA IDL program has been transferred to NSF, and the laboratories are called Materials Research Laboratories.

The IDL structure operates in parallel with other agency funding through the Principal Investigator grant system. Only a fraction (one-quarter to one-half) of the total support-costs of research by the IDL faculty are met by the IDL contract, and these are concentrated in supplying facility backups. laboratory equipment, technician support, and seed money for new starts. It is useful for a number of reasons to have outside relatively unbiased evaluations of individual research performance, and for the research ideas of the group to compete nationally rather than only locally for grant recognition. While there is considerable variance in the materials community regarding the effectiveness of the IDL program, it is generally accepted that in relation to its initial goals, the program has been largely successful. This question is discussed further in the university section.

Future Directions in Modes of Research Support: These comments have demonstrated a number of features of the present governmental research structure: (a) Aside from the general tightening of funds for the physical sciences, which has affected the field of materials as much as any other, the field of materials is generally in excellent shape. (b) Materials are deeply enmeshed within the governmental apparatus in a microscopic sense; the field has been characterized by much creative experimentation in management format to elicit a variety of mission goals, and it has been very successful in interacting with and contributing to the high technologies emphasized in the past. (c) Coordination between the federal agencies is reasonably good in terms of information sharing

From the management point-of-view, the government now faces a number of new challenges relative to materials. The nation possesses in the materials community an effective and tested component of technology. However, for the most part, the new urban-related technologies are developing in areas outside the traditional activities of materials specialists. A major question of strategy would then be to strive for a reassessment of goals by the materials community, and an examination of how the successful techniques and substantial talents of materials specialists can be properly utilized in these new directions. If the urban-related agencies were similar to the aerospace agencies, and if the period were still one of science and technology budgetary growth, the budgets of the new agencies could be expanded in familiar ways and traditional processes relied upon to bring about the desired results. However, a crucial point is that the total materials budget is unlikely to expand substantially in the absence of overall budget changes, so that the problem becomes one of reallocation of resources and talents.

This problem is a fundamental issue for all governmental agencies. Those presently possessing the major portions of the materials budget also possess the major materials management and technical abilities. Dismantling the present structure to build anew elsewhere will not only be painful, but more importantly will be wasteful and require many years to effect. Also, such changes carry the risk that a presently successful enterprise might not retain its vitality.

A recommended approach to this problem is to start with the present establishment, try to discover ways in which it can contribute to the newer areas through modifications, and then consider what new structures and formats are necessary. Specific recommendations are:

(a) In the future, materials people will be more deeply involved in the total technological evaluation and assessment process since the development of new technologies is going to have to be better prepared in the future than in the past. Thus, there must be better understanding of the total social and economic costs and benefits for coming major developments, such as widespread nuclear-power plants, new types of transportation systems, etc. Materials people, like most other applied scientists and engineers, are usually not constituted by intellectual background to deal with the social and political consequences of technology. They must therefore develop a greater ability to bring materials expertise into the decision processes wherein new technologies will be evaluated and planned. Workshop and study projects jointly sponsored by universities, government, and industrial groups would be a useful vehicle here.

(b) There are a number of cases where the newer agencies have developed special agreements with existing governmental laboratories to provide in-house research capability for the new mission. An example is the special relationship set up between HUD and the National Bureau of Standards on building research. These contracts and understandings are phrased in terms of the specific mission involved, and an opportunity exists for the materials community to develop the traditional kind of microscale involvement in the new areas through the materials groups of the laboratories concerned. Coordination of these activities through the Interagency Committee on Materials on an information-sharing basis should help develop and disseminate the new experience that the materials community will need in order to respond to the new problem areas.

(c) The universities materials community should be more intimately drawn into the new problem areas. While some of this will be done by standard and traditional technical projects, a broader approach is also available. The academic materials community has made some explorations of how to interact with the new problem areas, but needs to experiment, itself, with new groupings and ideas. In those universities where a major federal materials investment has occurred, such as the IDL's, these institutions should be encouraged to take on a major role in finding areas of promising materials research in the new problem directions, sponsoring workshops and conferences in the new program developments and examining the long-range changes necessary in the way we presently go about materials R&D. They should also experiment with research projects in materials as related to technological assessment, in the economic tradeoff problems, and in general modify their research programs in the light of apparent new materials challenges.

(d) Previous experience in successful materials research management has demonstrated the usefulness of a three-cornered interaction matrix between mission, in-house technical competence, and extramural programs. This experience suggests that the same combinations be continued with regard to new areas. Extramural funding can come from the mission agency itself, though there is relatively little research funding experience in most of the relevant agencies. It may also come through contract arrangements with other agency government laboratories which serve as the technical arm in a given field. The third possibility is that one of the traditional funding agencies, such as NSF, might serve in this capacity. All such formats are, of course, possible, and a variety of experimentation would be desirable. In any case, the extramural programs should be strongly coupled with in-government research competence.

(e) In order to bring about the difficult program modifications and necessary new adaptive program flexibility outlined above, the present coordination structures will have to be greatly strengthened, and a new policy-making responsibility established. The government should strive to insure that the materials community as a whole responds to the total national needs for new materials developments and research. This policy function should operate with close connection to the Office of Management and Budget, and be so arranged that it can respond to the perceived needs of the new programs as they develop in the civilian agencies.

National Goals and New Role of Materials Science and Engineering

The distribution of federal funds shown earlier indicates that defense, nuclear energy, and space technology have been the missions receiving the heaviest federal funds over the last few years. Additional and more "domestic" goals are emerging for the coming decade. Several of these will require a significant input from MSE and some suggestions on how to get the existing MSE community involved in this work were given at the close of the preceding section. The following describes briefly several of the social concerns in question:

Environmental Quality

The control of air pollution will often require new materials efforts. For example, work on the reduction of automobile emissions to meet projected standards requires high-temperature catalysts, combustion chambers, sensing and control units that can be produced reliably in great numbers.

Alternates to the internal combustion engine for automotive power all involve critical materials requirements. High-energy-density electric batteries are one of the more promising systems, but federal action and probably federal funding are required before they will be developed to the demonstration stage.

Another class of atmospheric-pollution problems centers around industrial combustion processes: for example, SO_2 in base-metal smelting operations or fossil-fuel-burning power plants. NO_2 presents a related problem. Satisfactory means of reducing or eliminating these emissions have yet to be found.

Governmental regulation is forcing industry to install, and sometimes develop, new equipment to alleviate these emission problems. However, in the past there has been little economic incentive to develop such processes, and so the technological base needed to develop improved processes is often lacking. As the environmental demands become more stringent, “off the shelf” items or their minor improvements will not be adequate, and new processes will be needed. An expanded, more coherent federal program aimed at providing the base technology for new emission control would be of substantial benefit.

Conservation of Resources

The goals of continued economic prosperity under the free enterprise system coupled with increased environmental concern and a diminishing supply of high-grade mineral resources has brought about a major change in previously accepted concepts. Escalating demands for quality products, the growing tendency to conserve mineral reserves, the higher costs associated with production, and the realization that recycling and reclamation of products are possible, all have led to this reassessment. Both the federal government and MSE have major roles to play in fostering the development of these concepts.

The government’s role in this new concept lies in granting economic incentives to stimulate commercial recycling enterprises. This could include a revision of the tax structure to allow a resource-recovery deduction; rapid plant and equipment decpreciation; subsidized trash and scrap collection; government-financed research; preferential transportation policies and rates; financial guarantees or loans; and material purchase guarantees.

The governmental research role could be to support pioneer innovations, while private enterprise could be responsible for its commercial adaptation. This would stimulate domestic industry and would provide the needed supply of materials at reasonable costs. All research—scientific, engineering, and economic—has to be directed to the entire industrial system of material production and use. The system includes primary and secondary production together with such elements as distribution, manufacture, use, disposal, and scrap collection. Subsystems exist within the system. For example, the recycling of lead and antimony used in automobile and industrial batteries is a fairly well-defined separate industrial system; platinum, gold, and silver tend to be recycled in closed systems for particular uses, while recycling of urban refuse is less organized and inherently more difficult to systematize.

Other subsystems that need more research and analysis include the recycling of the materials from automobiles, appliance components, and used structural shapes. The government, since it is probably the only agency having the capability to develop the statistical information needed, has an important role in this area, especially in view of its obligation to provide for the general welfare of the people who are the chief beneficiaries of such advances.

Clean Energy Supply

The Presidential Message to the Congress on June 4, 1971, included the following: “For most of our history, a plentiful supply of energy is something the American people have taken very much for granted. In the past twenty years alone, we have been able to double our consumption of energy without exhausting the supply. But the assumption that sufficient energy will always be readily available has been brought sharply into question within the last year. The brownouts that have affected some areas of our country, the possible shortages of fuel that were threatened last fall, the sharp increases in certain fuel prices, and our growing awareness of the environmental consequences of energy production have all demonstrated that we cannot take our energy supply for granted any longer.

“A sufficient supply of clean energy is essential if we are to sustain healthy economic growth and improve the quality of our national life. I am therefore announcing today a broad range of actions to ensure an adequate supply of clean energy for the years ahead. Private industry, of course, will still play a major role in providing our energy, but government can do a great deal to help in meeting this challenge.

“My program includes the following elements:

“To Facilitate Research and Development for Clean Energy:

“—A commitment to complete the successful demonstration of the liquid-metal fast breeder reactor by 1980.

“—More than twice as much federal support for sulfur oxide control demonstration projects in Fiscal Year 1972.

“—An expanded program to convert coal into a clean gaseous fuel.

“—Support for a variety of other energy research projects in fields such as fusion power, magnetohydrodynamic power cycles, and underground electric transmission.”

Energy-conversion systems (nuclear reactors, turbines, generators, etc.) invariably require that materials perform in new and demanding environments. Often materials problems limit the efficiency and performance of the unit. Consequently, materials R&D will play an essential role in the development of this program, and will be carried out in both industrial and governmental laboratories.

If one focuses primarily on electrical energy, the R&D effort has traditionally been supplied by equipment suppliers and the federal government. Recently the U.S. utilities have considered playing a significantly more active role than they have in the past. A recent report by the Electric Research Council lays out a broad program for utilities, manufacturers, and government.[11] The development of better, more reliable materials is an important theme in this report. A clear call is made for additional private, as well as federal, funding to support the work.

Building Materials

Many materials are used in the construction of buildings; these cover the whole spectrum of classes of materials, from low-technology materials, such as wood and concrete, to more sophisticated high-technology materials, such as plastics and composites. To identify materials needs and problems associated with buildings and construction technology, the following list provides a representative sampling of specific problems (prepared by experts in the National Bureau of Standards' Building Research Division) of primary importance in this area. These are not in order of priority.

Roofing Materials: There have been no recent innovations in this area. This may be partly due to the fact that no performance criteria or standards currently exist for roofing materials. This problem could be further complicated in the future, as there is a shortage of asphalt. It is estimated that 8×10^9 square feet of roofing material is used per year. Not enough use has been made of plastics or other substitutes.

Plumbing Materials: Plastics are potential replacements for metals. However, here again we need performance criteria and standards for plumbing systems. Additional research is required in the area of plastic pipes and tubings. This problem in the plumbing area has been a subject for comment and criticism by at least one Congressional Committee.

Joining Problems—Adhesives: Here much work is lacking in surface science and the science of adhesion. Adhesive manufacturers will not guarantee their products because not enough is known about the adhesive mechanisms. Current adhesives last only about four years as opposed to the desired 40 years.

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[11] Electric Utilities Industry R&D Goals Through the Year 2000, Report of the R&D Goals Task Force to the Electric Research Council, ERC Pub. No. 1–71, June 1971.

Sealants: These are used to provide more-or-less permanent joints between brick walls and ceilings or between marble slabs. Their main purpose is to exclude water and air. They require no structural properties, in contrast to adhesives, which bind one surface to another and must be capable of transmitting stress and strain. Better sealants are needed with greater imperviousness.

Acoustic Materials: Generally speaking, materials with good acoustic absorption do not have good moisture-absorption properties and also present a potential hazard with respect to fire safety. The best acoustic materials are not satisfactory, and further R&D work in this area is necessary.

Solar-Energy and Coating Materials: New materials are required for better solar-energy absorption, and coating transmission and reflectance properties. Current coating materials do not maintain these critical properties over a sufficiently long period of time.

Gasket Problems: This is somewhat related to the sealant problem. However, the gasket is usually coupled into a moving fixture such as a sliding door and may be subject to periodic compression and expansion. The need is for new rubberlike materials with improved resiliency and durability.

Moisture Effects: Moisture is a primary cause of deterioration in almost all classes of building materials, from concrete to metals. We need better materials that will resist the effects of moisture. Degradation of underground insulating materials due to moisture is a particularly serious problem. The corrosion of metals is another serious problem, particularly with respect to the corrosion of air-conditioning cooling towers.

MATERIALS EDUCATION AND RESEARCH IN UNIVERSITIES

Introduction

The marked diversity of the educational backgrounds of the professionals who work in the broad field of materials science and engineering has been emphasized earlier. It will be analyzed further in the final section on manpower of this chapter. The existence of this diversity, which had not been widely recognized hitherto, was identified early in the COSMAT study. Accordingly, it was concluded that a meaningful examination of university education and research in materials should take full account of such activities not only in those university departments that offer materials-designated degrees—such as in metallurgy, ceramics, polymer science, or materials science and engineering—but also wherever else such educational activities occur, i.e., in other university science and engineering departments and in interdisciplinary materials research laboratories.

This section of Chapter 7 describes our examination of that educational scope. Two summary points arising from this examination will perhaps clarify for the reader the wisdom of that broader approach in developing a proper understanding of university activities in materials. First, in the area of education (Table 7.28) for professionals working in the materials field, while the varieties of degree programs and academic institutions are large, formal undergraduate curricula in materials are found to be confined largely to students in the materials-designated departments. Yet, graduates from such departments make up only a fraction of the professional manpower in the materials field. Indeed, in the engineering disciplines alone (almost all of the materials-designated departments are within schools of engineering), the materials-designated bachelor's degrees are only some 2.5% of the total first-degrees in all fields of engineering, and the master's and doctorate's only some 3% and 8% respectively.[12]

Secondly, the materials research and the related graduate degrees from the materials-designated departments amount, in the early 1970's, to rather less than half of the materials research and graduate degrees involving faculty and students from other departments, i.e., to less than one-third of the total. In 1971, research support going directly to the materials-designated departments (of which there are almost 100) totaled some $17 million, compared to about $51 million funded to interdisciplinary materials centers and their associated faculty. (Only about one-third was direct or "block" support to the centers; the remainder was direct support to individual faculty members.) Four million dollars of the block support was assigned

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[12] The data on which these figures are based are derived from the annual statistics on engineering degrees from the U.S. Office of Education, American Society for Engineering Education, and the Engineering Manpower Commission. The difficulties occasioned from the changing definitions "materials" degrees in these statistics have been discussed by Radcliffe (J.Metals (May 1969) 29–35).

TABLE 7.28 Types of Education and Institutions from which Manpower in the Materials Field Is Derived

TYPE OF EDUCATION	PRINCIPAL ACADEMIC INSTITUTIONS INVOLVED	PRINCIPAL USER INSTITUTIONS FOR GRADUATES
I. Terminal B.S. in	State and private universities	Production & development in materials producing and consuming industries.
a) Met., Cer., Poly. Sci.		
and		
b) Mech. Eng., Ind. Eng., Civil Eng., Chem. Eng., Physical Sciences		
II. Preparatory B.S. in Mat. Sci., Met., Cer., etc. `	State and private universities involved in materials research	
+ fraction of Physics, Chem., Main Eng. Disciplines `	All research universities	Graduate schools
a) Headed for advanced degrees in Materials Science.		
b) Headed for advanced degrees in related fields		
III. Terminal M.S. as in I	Major state and private universities	Development & research in moderate-to-large organizations
IV. Ph.D.'s as in II		
a) Mat. degrees in many fields, esp. Mat. Sci.	Selected universities esp. involved in materials	Research & development in materials consumer and producer industries, government; university teaching
b) All other related depts.		
V. 2-yr. Technicians	State universities, community colleges, other institutions	Producing industries

to faculty in the materials-designated departments for a total of approximately $21 million. The university materials centers, which were started in the early 1960's with the formation of interdisciplinary laboratories (known as IDL's) in 12 universities through the Department of Defense, have increased in number to about 28. In 1971, the original 12 universities received approximately two-thirds of the total direct federal support for all university materials R&D.

The scale of the activities of the materials research centers and their associated faculty, as indicated by the foregoing, merits some discussion of how the centers came into existence, as a precursor to outlining the scope and rationale for the particular analysis of materials activities in the universities which was adopted by COSMAT.

The materials-related disciplines were the focus of the first attempt on the American university campus to create a new style of research organization and to accelerate the processes of academic curricular change resulting from federal recognition of a specific national need. At the time that physical metallurgy and the physics of metals were the principal, and largely separate, areas of materials research at universities in the late 1930's and 40's, the concept of task-oriented, closely coupled, interdisciplinary research was being developed in a particular sector of U.S. industry: namely, the research laboratories of the major corporations related to the electronics, communication, and aerospace industries. Such industrial prototypes served as the models for governmentally inspired changes at the universities (although industry had little direct input into the actual formulation of the programs). The federal initiative in the materials research area stemmed from advisory reports which identified the need for increased manpower for such materials research but which also stressed that the university laboratories could not afford the sophistication of industrial research because of the large investments required in equipment and manpower. The Coordinating Committee on Materials Research and Development (CCMRD) proposed specific action to the Federal Council on Science and Technology in 1959. As a consequence, the Advanced Research Projects Agency of DoD developed programs in 12 universities for "Interdisciplinary Materials Research Laboratories." The AEC supported analogous laboratories in 3 universities, and NASA followed with a smaller program. Subsequently, several universities established similar centers without special or continuing support, so that a total of some 28 materials centers now exist on U.S. campuses. The creation of this system of interdisciplinary materials research laboratories and the strong growth of many of the materials-designated and materials-related departments resulted from federal initiative and from investments of $300—$400 million during the ensuing decade. This effort in the materials field is probably the most widespread and longest established attempt at encouraging interdisciplinary concepts and practices within universities. It has over a decade of history, and now that other fields of similar scope are emerging, an evaluation of MSE in our educational institutions is especially timely for the use of both university administrators and federal officials concerned with research policy.

From the above introductory discussion, it is apparent that an analysis of university education in materials requires a study of the following principal areas:

(a) Instructional activities related to MSE, including materials-designated degree programs and educational activities in disciplines related to materials.
(b) Materials research, as conducted in the materials research centers and academic departments.
(c) Institutional interactions, including the management of materials research and coupling between the universities and industry.

Because the very grouping of activities entitled materials science and engineering is only somewhat more than ten years old, comprehensive statistics, data, evaluations, and even a definitive list of the departments or degree programs proved to be unavailable. Accordingly, several questionnaires were designed to obtain the necessary data on materials-related university research and educational activities. (In interpreting this information, care has been taken to try to recognize the inevitable shortcomings of data-gathering for a new area where common definitions are not yet adequately established.) The four questionnaires that were adopted and the relevant response characteristics were as follows:

(1) Questionnaire to all departments in the U.S. granting materials-designated degrees regarding their undergraduate and graduate teaching and research activities. The responses (72 out of 112 questionnaires sent) cover the institutions granting 95% of all doctorates in such departments.
(2) Questionnaire to all departments granting degrees in fields related to MSE, i.e., Chemistry (64%), Physics (70%), Geology (45%), Chemical Engineering (42%), Civil Engineering (33%), Electrical Engineering (53%), Mechanical Engineering (42%), which were listed in the top two categories of the Roose-Anderson report evaluating graduate departments.[13] (Shown in parentheses are the percentage of responses in the various fields.)
(3) Questionnaire on the research activities of all the formally designated interdisciplinary materials research centers in the country. Twenty-eight such centers were located (100% response).
(4) Questionnaire seeking individual opinions of the effectiveness of materials centers from a set of senior university, governmental, and industrial representatives in the materials field. The set used was the membership of COSMAT, its panels, the membership of the National Materials Advisory Board, and the Chairmen (only) of the NMAB major committees for the last decade. (About 40% response)

Samples of the questionnaires are provided in Appendix 7A.

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[13] K.D.Roose and C.J.Anderson, A Rating of Graduate Programs, American Council of Education, Washington, D.C. (1971).

Before proceeding with the analysis of the response data based on the above questionnaires, we shall sketch some historical highlights of materials education in the U.S.

Some Historical Highlights of Materials Education in the United States

A broad perspective of education in the materials field is aided by recognition of the sequence in which the use of the major classes of materials must have developed. If prehistoric times are considered, there is no doubt that man's dependence on, and hence his concern with, polymeric materials (natural fiber and wood for clothing and shelter) far predates his use of any other type of material, including ceramics (Stone Age) and metals (Bronze Age). Formal education in the science and engineering of any of these materials could not, of course, develop until science and engineering themselves took form in comparatively recent times. Yet, it is interesting to note that many pure sciences were born out of applied science; materials technology was in many ways the precursor of much physical science just as the beginnings of chemistry were grounded in extractive metallurgy. The formation of disciplines within the materials family undoubtedly arose in an order dictated by many factors, but one may speculate that foremost among these were the complexity of the chemical manipulations required to isolate useful materials, and the urgency with which they were needed.

If this is so, the reasons for the preoccupation of materials-science education with metals become clear. Most metals, as used, are nearly pure elements or relatively simple mixtures of them, at least up to very recent times. The processes needed to produce them from their naturally-occurring ores are also simple, again with some notable exceptions such as the electrolytic production of aluminum. The interest of the alchemists in precious metals must have contributed much to the early stages of the science of metallurgy. Additionally, the accessibility of metals, the relative ease with which they can be processed, and their serviceability in answering man's needs for materials provided the impetus for the early development of the science and engineering of metals, which we now call metallurgy.

Ceramics, on the other hand, are both more complicated chemically and much less tractable. The need for these materials was great in certain areas related to metals processing, such as the refractory materials used to line furnaces or molds. Therefore, a limited portion of the science and engineering of ceramics grew up concurrently with the rise of metallurgy. Other parts of the empirical approach to manipulating brick, clay, sand, and cement chiefly into construction materials developed as a specialized branch of chemistry or chemical engineering. However, the basic science of ceramics has been some two or three decades behind that of metallurgy, principally because of the greater variation of ceramic structures on the atomic scale.

In striking contrast, organic polymers or macromolecules are materials of enormous chemical complexity, whose basic long-chain nature was still in doubt even in the 1920's. Thus, polymer science and engineering has of necessity developed even more recently, and education in this field came after the systematization of metallurgy and ceramics.

Hence, it is not surprising that the first of the several materials disciplines to advance to the point where separate educational programs and curricula could develop was metallurgy. With the increased tempo of technological advances together with the proliferation of scientific and engineering knowledge, and the consequent need for specialization, formal education in MSE began in separate departments or subdepartments (often within chemistry or chemical engineering) or in schools of mining or mineral products in the early years of the present century. The early departments were also concerned to a lesser extent with nonmetallics, for the reasons cited above.

The Morrill Act of 1862 establishing the Land-Grant Colleges for training to meet society's obvious needs in "Agriculture and the Mechanic Arts" was a landmark which signalled the beginnings of the great State universities of the U.S. Because of their mandate to supply manpower to the developing materials-industrial base of the nation, these institutions were to produce a large percentage of the trained materials specialists of the country—from the Colorado School of Mines to the State Universities of Michigan, Illinois, Ohio, and Pennsylvania. Other early materials departments were closely associated with specific local industries in which their graduates expected to find employment. Thus, well-established departments of metallurgy grew up in the major centers of the steel and nonferrous industries (Lehigh in Bethlehem, Carnegie-Mellon in Pittsburgh, Case Western Reserve in Cleveland, Illinois Institute of Technology in Chicago). In some of the earlier departments to be formed, the faculty took a national rather than local view of the industry which they were serving. They developed close associations with some of the major metal industries across the country. Notable in this group were Columbia and Yale. One of the few examples of a department being established because of the needs of a metals-consuming industry is that of Rensselaer Polytechnic Institute near the main plant of the General Electric Company in Schenectady.

Some of the early departments of metallurgy had some faculty who specialized in ceramics. As the science of ceramics developed, the subgroups within metallurgy departments which were concerned with this subject tended to expand and in some cases to separate themselves from the parent department. Before the Second World War, some 16–20 such groups existed. However, in those states where the refractory, whiteware, glass, and related industries were important, the ceramics section or departments tended to grow parallel to the metallurgy effort and sometimes in competition with it, e.g. at the Universities of Illinois, Ohio State, and Penn State. About a half-dozen institutions carried on a very large fraction of the nation's education in ceramic science and technology (including, in the case of Alfred University, some work on the aesthetic and artistic development of these materials).

The early educational efforts related to polymers were largely descriptive rather than scientific, since they predated the development of polymer science and engineering. Courses in the technology of polymeric materials were developed as long ago as 1908 for the paper industry, and subsequently in the 1920's and 1930's for the textile, rubber, and paint and varnish industries. Emphasis on plastics per se came later still, for these are largely synthetic materials whereas the above-mentioned industries were originally based entirely on naturally-occurring polymers. It was not until the late 1930's that the research on polymerization, carried out chiefly in industrial laboratories, provided a sound basis for the science of synthetic polymers. Organized curricula treating polymers as a science developed only after the Second World War, by which time the dependence of industry on polymeric materials was firmly established; for example, in electrical insulation for radar and television use, and rubbers for seals, gaskets, hoses, and tires. Most of these curricula have remained within the parent departments (again usually chemistry or chemical engineering) with a few notable exceptions. The first separate effort to achieve prominence was at the Polytechnic Institute of Brooklyn, with others formally organized more recently (chiefly after 1960) in the Universities of Akron, Case Western Reserve, and Massachusetts, and informally at Rensselaer Polytechnic Institute and at various industry-oriented institutions such as paper and textile institutes. In general, these departments or subdepartments concerned with polymeric materials have had little or no connection with the older metallurgy/ceramic departments. Starting in the 1960's, however, departments which grew out of metallurgy and aspired to cover materials more broadly have added courses in ceramics and polymers to their curricula.

The materials departments established before 1930 were often associated organizationally or conceptually with chemistry or chemical engineering and most of the faculty were drawn from those backgrounds. In a few places, the organizational link with chemical engineering has been maintained, as for example at Syracuse University. Yet, for the most part the academic development has not remained closely associated with the development of chemistry, and in some instances (e.g. at the University of Michigan), a long-standing link with chemical engineering has been severed. Once formed, the materials departments have tended to be little influenced by the parent chemical discipline. Moreover, after 1930 a major change occurred. The advances in solid-state physics started to exert a much greater influence on the content of curricula in materials. The flowering, first of metal physics and then of semiconductor physics, provided a great challenge for, as well as a great impact on, pedagogy in the materials field. Since 1960 the trend towards higher-bandgap materials has further emphasized physical inquiry on ceramic or semi-insulator materials. Most of the groups concerned with polymers also started, as stated earlier, in chemistry or chemical engineering departments; they, too, have been absorbing more from the discipline of physics in recent years.

Developments within materials departments have also been influenced, to a large extent, by the changes in general attitude and approach to undergraduate and graduate education in engineering. All of the early programs were designed to produce a qualified and professional metallurgist or ceramist at the bachelor's level. Many of the graduates of such programs went directly into industry and were expected to be useful engineers very shortly after graduation. The early graduate programs were designed to lead to the doctorate and from the beginning had a strong science orientation. One trend in engineering generally over the last ten years has been to push the primary professional qualification to the master's level. The undergraduate degree has, therefore, tended to become a more general type of education and a suitable basis for further work in a variety of professions. To some extent, the development of materials-degree programs along these lines has lagged behind those in other areas or engineering; there remains a strong inclination for such departments to seek accreditation for their respective bachelor's degrees as the first professional qualification.

Let us now turn to describing the materials teaching and training activities associated with:

(a) Degrees carrying the formal designation of materials science and/or engineering, or any one of the material classes (metallurgy, ceramics, polymer science); and
(b) Degrees in all the materials-related sciences and engineering disciplines.

Instructional Activities

In every field of technology, the contribution of universities to society is educated manpower. Correspondingly, the field of materials draws on the products of the universities' instructional activities from several disciplines and in two major categories: (a) those departments or degree programs which are formally designated as materials (i.e. materials science, solid-state science, materials engineering, metallurgy, ceramics, polymer science and/or engineering) and hence, are wholly dedicated to the field; and (b) the materials-related disciplines which also contribute in a substantial way to the development of the field, but each of which is only partly concerned with materials as such. Corresponding data from a wide variety of university and manpower statistics (from the National Science Foundation, Engineering Council for Professional Development, Engineering Manpower Commission, the National Academy of Sciences) have been analyzed in addition to the new data obtained from the COSMAT questionnaires in order to develop the following account.

Materials-Designated Departments

In Table 7.29 are listed 89 U.S. universities with their degree programs designated as in the materials area. The degrees include metallurgy, metallurgical engineering, ceramic engineering, metallurgy and materials science, solid-state science, materials science, and polymers. Of these 89, at least 45 have graduate or undergraduate programs with the word materials in the title, as part of a phrase such as materials science, materials engineering, solid-state science (taken to be equivalent to materials science). There are 31 programs with titles involving only metallurgy, though 8 of the 14 materials and solid-state science programs have evolved from those in metallurgy. In contrast, there are only 14 degree programs in ceramics and 4 in polymerics (not including degrees in chemistry with specialization in polymers), in spite of the current wide use of the latter materials.

These program titles have changed significantly in the last decade; in 1960, there were virtually no programs with the word materials in the title. Table 7.30 lists the titles existing in 1964 and 1970 as simple evidence of this change.

TABLE 7.29 Materials-Designated Degree Programs[+] G=Grad; U=Undergrad; B=Both; #=Also has interdisciplinary research center

	CERAMICS	METALLURGY	POLYMERICS	MATERIALS (Departmental) *denotes hybrid title, usually with Met.	MATERIALS (Interdiscip.)	PART OF LARGER UNIT[++]
Akron #			G			
Alabama		B				
Arizona		B				
Brooklyn Polytech.		B				
Brown #						B
California, Berkeley #				B		
California, Los Angeles				B*		
California State Polytech. College		B				
California, San Jose				B		
Carnegie-Mellon				B*		
Case Western #			G	B*		
Chicago #						
Cincinnati				B		
Clemson	B				G	
Cleveland State		B				
Colorado Mines		B				
Columbia						B
Connecticut #		B				
Cornell #				B		
Delaware		U				
Denver				G*		
Drexel		B				
Florida				B*		
Georgia Tech	B	G				

G=Grad; U=Undergrad; B=Both; #=Also has interdisciplinary research center

	CERAMICS	METALLURGY	POLYMERICS	MATERIALS (Departmental) *denotes hybrid title, usually with Met.	MATERIALS (Interdiscip.)	PART OF LARGER UNIT++
Grove City		U				
Harvard #						B
Idaho		B				
Illinois Chicago Cir.				B*		
Illinois, Urbana #	B	B				
Illinois Tech.				B*		
Iowa State	B	B				
Kentucky				B*		
Lafayette		U				
Lehigh #				B*		
Marquette					B	
Maryland				G*		
Massachusetts #			G			B
M.I.T. #	G	G		B*		G
Michigan				B*		
Michigan State				B*		
Michigan Tech.		B				
Minnesota						B
Mississippi State				B		
Missouri-Rolla #	B	B				
Montana College Min. Sci.		B				
Nebraska						B
Nevada		B				
New Mexico Institute						B

G=Grad; U=Undergrad; B=Both; #=Also has interdisciplinary research center

	CERAMICS	METALLURGY	POLYMERICS	MATERIALS (Departmental) *denoted hybrid title, usually with Met.	MATERIALS (Interdiscip.)	PART OF LARGER UNIT++
New York State, Alfred	B					
New York State, Stony Brook				G*		
New York University				B*		
North Carolina State	U			B*		
North Carolina University #						
Northwestern #				B		
Notre Dame				B*		
Ohio State	B	B				
Oklahoma		B				
Oregon State		B		G*		
Penn State #	B	B	U		G	B
Pennsylvania #				B*		
Pittsburgh				B*		
Princeton					G	
Purdue #				B*		
Rennselaer Poly. #				B*		
Rice #				B*		
Rochester					G	
Rutgers	B					
So. California #				B*		
South Dakota Mines		B				
Stanford #				B		
Stevens		B				

G=Grad; U=Undergrad; B=Both; #=Also has interdisciplinary research center

	CERAMICS	METALLURGY	POLYMERICS	MATERIALS (Departmental) *denoted hybrid title, usually with Met.	MATERIALS (Interdiscip.)	PART OF LARGER UNIT[++]
Syracuse					G	
Tennessee						B
Texas						B
Texas (El Paso)		B				
U.S. Naval Acad. (Post Grad)						B
Utah #		B		B*		
Vanderbilt				B*		
Virginia				B		
Virginia Polytech.	B			G*		
Washington #	B					
Washington State	B	B				
Washington University St. Louis #					G	
Wayne State		B				
West Virginia						B
Wisconsin, Madison #		B			G	
Wisconsin, Milwaukee				B*		
Yale						B
Youngstown U.				B*		

[+] These data are combined from reports of ECPD, the Engineering Manpower Commission, NSF Report 71–27 and J.Nielsen's Education Yearbook.

[++] Programs are typically combined with Chem. Eng. (Ch), Mech. Eng. (Mech) or part of a goal, Engineering (Eng) or Applied Physics (AP) degree.

TABLE 7.30 Materials-Designated Departmental Title Changes from 1964 to 1970

A. U.S. Schools with Metallurgy Faculties

Departmental Title	1964		1970	
Mining and Metallurgy	1		–	
Mining and Metallurgical Engineering	3		–	
Mining Engineering and Metallurgy	1		1	
Mining, Metallurgical, and Petroleum Engineering	1		1	
Mining, Metallurgical, and Mineral Engineering	1		1	
Mining, Metallurgical, and Ceramic Engineering	–		1	
		7		4
Minerals and Metallurgical Engineering	1		–	
Mineral Technology	1		1	
Mineral Engineering	–		1	
Metallurgical and Mineral Engineering	–		1	
		2	3	
Ceramic and Metallurgical Engineering	1		–	
Metals and Ceramic Engineering	1		1	
		2		1
Metallurgy	9		7	
Metallurgical Engineering	21		13	
Physical and Engineering Metallurgy	–		1	
Institute for the Study of Metals	1		–	
Metallurgy and Materials Science	2		7	
Metallurgical Engineering and Materials Science	1		2	
Metallurgy and Materials Engineering	1		2	
Metallurgy, Mechanics, and Materials Science	1		1	
		36		33
Materials Science and Engineering	1		2	
Materials Science and Metallurgical Engineering	–		3	
Materials and Metallurgical Engineering	–		1	
Materials Science	4		6	
Materials	–		2	
Materials Engineering	1		3	
		6		17
Carry Forward		53		58

A. U.S. Schools with Metallurgy Faculties				
Departmental Title	1964		1970	
Carried Forward		53		58
Chemical Engineering (with materials)	10		10	
Mechanical Engineering (with materials)	4		6	
Engineering (with materials)	2		4	
		16		20
Total Departments:		69		78
Total Associated Metallurgy/Materials Faculty:	522		758	
Total Associated Metallurgy/Materials Graduate Students:	1583		2222	
Total Associated Metallurgy/Materials Seniors:	864		851	
B. U.S. Schools with Ceramics Faculties				
Departmental Title	1964		1970	
School (College) of Ceramics	2		2	
Ceramic Engineering	7		6	
Ceramic Technology	1		–	
Mineral Engineering	1		–	
Mineral Technology	–		1	
		11		9
Ceramic and Metallurgical Engineering	1		–	
Materials Program	1		1	
Metals and Ceramic Engineering	–		1	
Mining, Metallurgical, and Ceramic Engineering	–		1	
Metallurgy and Materials Science	–		1	
Materials Science and Engineering	–		2	
Materials Engineering	–		2	
Engineering	–		1	
		2		9
Total Departments:		13		18

Total Associated Ceramics Faculty:	76	136
Total Associated Ceramics Graduate Students:	265	307
Total Associated Ceramics Seniors:	222	253

(Data taken from the series of Education Yearbooks by J.P.Nielsen)

An overall description of all the materials-degree programs at U.S. universities is given in Table 7.31. It is striking that, in view of the changing titles of the programs discussed above, there appear to be only a very few (less than 10) really new programs. Not all of these are interdisciplinary in nature, and most of them are small. In general, the constraints of the university structure make it easier to modify existing programs than to start new ones, and it is more difficult to operate in an interdisciplinary fashion than within existing departmental frameworks. Nevertheless, two or three strong new interdisciplinary programs have emerged. Other points to note are the frequency (55%) of cases in which the graduate enrollment is larger than the undergraduate; the predominance of metallurgy backgrounds among the faculties; and the concentration in industry as the first employers of graduates with advanced degrees.

While new programs typically appear to lean towards science, more program titles contain the word engineering than science in cases where only one of these words is mentioned. Curricula in metallurgical or ceramic engineering are among those with the largest undergraduate enrollments in any of the MSE programs ("engineering" in this context usually means a concern with the technology of the production and application of a designated class of material together with some understanding of the science relevant to the technology). In these programs, there is frequently considerable emphasis on laboratory courses and nearly all of them contain a project or dissertation requirement in the final year. However, the laboratory courses in the junior years tend to be traditional and the final-year projects are often small laboratory experiments reflecting the scientific, rather than the engineering, interests of the supervisor. Relatively few projects were discovered which were intended to give the senior student a realistic experience of modern problem-solving design engineering. At the graduate level, few of the materials-designated programs seem to have a substantial engineering or technology content; more often they can be described as applied-science-oriented. Less than a dozen D. Eng. or equivalent doctoral degrees have been awarded in materials in any recent year, the Ph.D. and Sc.D. being overwhelmingly more popular where there is a choice. Similarly, where a department offers both science and engineering options, the latter is typically less popular and may amount to only a paper exercise. It also seems more difficult to design engineering courses which deal with all types of materials rather than just one. These characteristics of the curricula are significantly at variance with the emphasis being sought by some industrial employers.

The distribution of faculty in materials departments among the full, associate, and assistant professorships as a function of departmental size is similar to that in other departments of science and engineering schools. The proportion of tenured faculty also appears to be in the expected range. In the majority of departments, a high percentage of the faculty members have Ph.D. degrees.

Table 7.32 shows the relation between graduate faculty and postdoctoral staff for materials-designated departments compared to that of all physical sciences and all engineering. Although intermediate, the proportion of postdoctorals in materials is closer to that in the sciences than in engineering, again reflecting the strong science orientation of the graduate materials programs.

TABLE 7.31 Data on Materials-Designated Degree Programs (Listed in order of average number of Ph.D.'s/yr)

STUDENTS												FACULTY												
							First employers of 1971 M.S. + Ph.D. graduates									Field (%)								
No. Jr-Srs (av.)	No. Grad. Stud. (av.)	Total Students (av.) (Upperclass + Grad)	No. BS/yr (av. 5 yrs)	No. MS/yr (av. 5 yrs)	No. Ph.D. (av. 5 yrs)	Total No. Degrees (av. last 5 yrs)	% Industry	% Government	% University	% Other	Postdoctoral	Total Faculty	FTE Faculty	Tenured	% with Ph.D.'s	Materials Sci.	Materials Eng.	Metallurgy	Ceramics	Polymerics	Chemistry	Physics	Engineering	Other
37.8	146	184	14.6	12.4	29.8	57	75	3	17	5	4	30	28	21	97	–	–	56	10	–	17	17	–	–
74	146	220	35.4	14.6	24.6	75	53	7	28	12	24	37	28	27	95	8	–	22	8	5	24	14	8	8
49	115	164	27.4	16.0	16.8	60	73+	3	18	6	10	21	21	15	95	– –	– –	70 –	20 –	– 40	– 30	10 20	– 10	– –
49.6	97	147	24.6	14	14.8	53	72	16	12	–	2	22	18	12	100	6	15	30	6	8	10	8	5 7	5
14.2	89	103	5.2	7.6	14	27	35	7	43	–	16	17	17	15	100	13	–	47	6	12	6	12	6	–
–	104	104	7.8	3.8	13.4	25	85	10	5	–	7	16	16	12	94	7	14	44	14	–	7	14	–	–
75	86	161	32.2	15.6	13.0	51	71	19	10	–	NA	27	16	22	88	– 8	– –	53 –	– 50	– –	7 8	20 8	20 8	– 17
125	87	212	25.2	17.8	12	55	70	8	22	–	37	22	7	20	100	8 –	– –	46 –	– 78	– –	15 11	8 11	23 –	– –
1	81	82	1.6	16.6	11.8	30	40	50	10	–	9	15	13	13	100	20	–	20	–	7	20	33	–	–
53	68	121	26.6	21.0	9.8	57	85	4	4	7	6	20	9	16	100	7	3	4	2	0	1	1	0	2
56	26	82	26.4	3.6	8.6	39	84	9	7	–	2	11	9	6	80	–	–	–	70	–	–	20	–	10
32.4	47	79	25.4	17.8	8.0	51	65	15	20	–	1	15	15	10	86	7	–	62	–	–	14	17	–	–
13.8	56	70	11.4	5.8	8.0	25	58	6	24	12	10	13	13	9	92	74	–	46	–	–	8	30	12	–
11.4	52	63	5.8	4.8	7.6	18	49	3	45	3	8	13	13	11	100	8	–	76	–	–	8	8	–	–
87	55	142	41	18.4	6.2	66	80	15	5	–	3	18	16	16	55	– –	– –	63 –	9 71	– –	– –	9 14	9 –	– 14
23	29	52	9.6	9.0	6.0	25	60	10	15	15	4	15	13	14	93	7	–	40	13	13	13	7	7	–
39.4	53	92	16	16.8	5.6	38	62	8	15	15	2	16	15	10	91	38	–	31	–	–	–	13	19	–
16.8	41	58	6.0	6.0	5.2	17	38	21	18	23.3	50	18	17	12	90	–	–	40	10	–	10	20	5	15
55.8	60	116	24.2	9.8	4.6	39	70	10	20	–	3	14	13	55	76	28 –	– –	44 –	– 67	– –	– –	14 16	14 16	– –
15.6	30	46	–	9	4	13	65	1	5	26	4	27	27	15	80	–	4	67	–	15	7	–	4	–
–	17	17	–	4.4	3.6	8					0	12	6	7	92	–	–	75	–	8	8	8	–	–
	24	24	12.2	2.4	4.2	19	44	21	35	–	6	10	10	7	100	–	–	2	–	1	3	3	–	1
23.8	17	41		3.0	3.4	6	73	0	20	–	2	7	9	6	100	17	–	83	–	–	–	–	–	–
	32	32	13.2	7.6	2.6	23	75	20	–	5	20	11	10	7	100	–	–	–	–	–	33	33	33	–
26.4	29	55	20.8	5.8	2.6	29	75	10	15	–	4	14	10	4	86	36	–	55	–	–	–	9	–	–
54	27	81	1.4	8.2	2.6	12	30	14	37	19	2	13	13	12	85	16	–	56	7	–	7	7	7	–
2.8	9	12	6.6	0.4	2.4	9					3	4	4	4	100	1	–	3	–	1	–	–	–	–
13	15	28	5.6	2.8	2.0	10	39	9	48	4														
11.6	15	27	2.6	3.2	2.0	8	67+	13	20	–	0	7	6	7	86	–	–	–	100	–	–	–	–	–

STUDENTS							First employers of 1971 M.S. + Ph.D. graduates					FACULTY				Field (%)								
No, Jr-Srs (av,)	No, Grad. Stud. (av.)	Total Students (av.) (Upperclass + Grad)	No. BS/yr (av. 5 yrs)	No. MS/yr (av. 5 yrs)	No. Ph.D./yr (av. 5 yrs)	Total No. Degrees (av. last 5 yrs)	% INDUSTRY	% GOVERNMENT	% UNIVERSITY	% OTHER	Postdoctoral	Total Faculty	FTE Faculty	Tenured	% with Ph.D.'s	Materials Sci.	Materials Eng.	Metallurgy	Ceramics	Polymerics	Chemistry	Physics	Engineering	Other
12.6	20	33	23.6	0.4	2.0	26	50	-	50	-	2	22	14	10	20	2	-	4	2	1	5	2	-	-
47.6	18	66	6.2	7.8	1.6	16	45	22	33	-	3	10	10	8	90	-	-	70	-	10	10	-	10	-
12.6	14	27	14.2	4.6	1.6	20	70	20	10	-	0	6	4	6	6	-	-	83	-	-	-	17	-	-
28	18	46		8.6	1.6	10	69	5	26	-	0	12	8	4	75	-	-	25	8	-	8	17	25 8	-
26	15	41	11.2	2.2	1.4	15	80	-	20	-	1	7	7	5	100	-	-	6	1	-	-	-	-	-
	21	21		6.2	0.8	7	57	14	3	26	1	10	12	7	70	30	-	20	-	-	10	20	10	10
114	20	134	48	9.4	0.6	58	90	-	-	10	1	19	15	6	79	21	16	53	5	-	5	-	-	-
15.4	14	29	5.2	3.6	0.2	9	-	-	-	-	3	10	10	7	90	30	-	50	10	-	10	-	-	-
40.2	24	64		6.0	0.1	6	22	22	44	11	1	8	8	1	87	13	-	13	25	-	13	25	-	13
24.4	8	32		3.4	0	3	50	20	20	10	0	5	5	4	100	-	-	40	100	-	-	-	-	-
9	2	11	4.8	2.6	0	7	75	-	-	-	0	3	0	3	67	-	-	100	-	-	-	-	-	-
9.6	8	18	3.8	2.8	0	7					NA	4	4	NA	100	25	-	50	25	-	-	-	-	-
8.8	3	12	2.8	1.6	0	4	80	3	0	-	0	3	3	0	66	-	-	7	-	-	-	-	33	-
17.2	16	33	6.4	5.8	0	12	80	20	0	0	NA	8	8	8	90	-	35	50	15	-	-	-	-	-
13.2	2	15	7.0	4.8	0	12	85	5	10	-	0	6	5	NA	3	50	-	50	-	-	-	-	-	-
5.4		5	2.4			2					NA	22	NA	13	100									
											0	4	4	3	75	25	25	75	-	-	-	-	-	-
16.2		16	8			8					1	6	6	5	100	-	-	59	-	16	-	25	-	-
											1	14	11.5	9	93	-	9	38	38	-	-	15	-	-
18	6	24	4.3			4					0	8	8	7	88	20	-	60	10	-	-	-	-	-
43.6	6	50	11.2			11	80	4	12	4	0	13	7	1	90	30	10	40	5	5	5	5	-	-

A. <u>Totals from COSMAT Returns</u>

1409 1868 3292 588 348 259 1182 655 532

B. <u>National Totals</u> (from other sources)

∿920 ∿460 ∿270 749

Percentage A/B x 100

64% 76% 96%

TABLE 7.32 Full-time Faculty and Postdoctorals, 1970

	Total Faculty	Graduate Faculty	Postdoctorals
All fields	58,022	49,332	8,940
Engineering	11,830	9,985	791
Metallurgy and Materials	622	583	125
(Percent of all Engineering)	(5.3)	(6.8)	(15.8)
Physical Sciences	10,925	9,785	3,730

The size range of undergraduate enrollments in relation to the number of full-time equivalent (FTE) faculty in the materials-designated departments is shown in Figure 7.22. The data scatter widely, but the spread is reduced when the combined graduate and undergraduate student enrollment is considered, as in Figure 7.23. The faculty-student ratio is still high, at about 1 to 10 and is rather insensitive to the size of the department. In terms of total number of students, there are two large departments with more than 200 students; 25 departments having between 50 and 200 students; and 20 small departments with less than 50 students.

Graduate enrollments in materials-designated departments and their percentages of those for the corresponding engineering schools are shown in Figure 7.24 which indicates that the proportion of materials students has not changed much over the period 1967–1971. The proportion of foreign graduate students (Figure 7.25) is approximately 30% overall, compared to 20% among graduate students in physical sciences, 36% among graduate students in engineering, and 41.6% among materials-designated graduate students, as reported recently (NSF 1971, No. 71–27). In the latter report, only the materials-related fields of mining, agriculture, and petroleum engineering had more foreign graduate students than the materials-designated fields.

The data in Tables 7.33 and 7.34 show the proportion of graduate students by type of support and by the sources of federal support (data derived from NSF 71–27). The proportion of research assistants in metallurgy and materials (56.5%) is the highest in all engineering and in all fields, and the fraction of support from DoD (33.8%) and AEC (21.5%), for graduate students in metallurgy and materials is also higher than for other fields.

The size distribution of materials-designated departments in terms of number of doctoral degrees granted is illustrated in Figure 7.26. These results (taken from Engineering Manpower Commission, 1971) pertain to a median department size of 21–30 students. Of the 51 departments with doctoral programs in materials, 2 awarded 20%, 8 awarded 50%, and 19 awarded 75%. Over a quarter of the departments graduated 5 or less Ph.D.'s in 1970–71. The questionnaire data on this point (Figure 7.27) indicate an even larger proportion graduated by the larger schools.

The distribution among materials-designated departments of doctor's master's, and bachelor's degrees awarded is shown in Figures 7.27, 7.28, and 7.29, respectively (Questionnaire data). The distribution of B.S. degrees is similar to that reported in the Nielson Education Yearbook (1969) for the number of senior students in 85 metallurgy departments. Of the 49 departments reporting undergraduate data in the COSMAT questionnaire, 25 graduated less than 10 students per year averaged over the period 1967–1971, whereas two awarded more than 45 B.S. degrees per year and two more between 30 and 40. Among these four, however, there was little correlation between the sizes of the undergraduate and graduate programs, only one department having large numbers in both groups.

Among the departments awarding materials-designated Ph.D. degrees, the largest producer graduated 30 per year on the average, and only two others awarded more than 15 per year. Of the 50 departments reporting, 24 awarded fewer than 6 Ph.D.'s per year, but some of these had relatively large undergraduate enrollments.

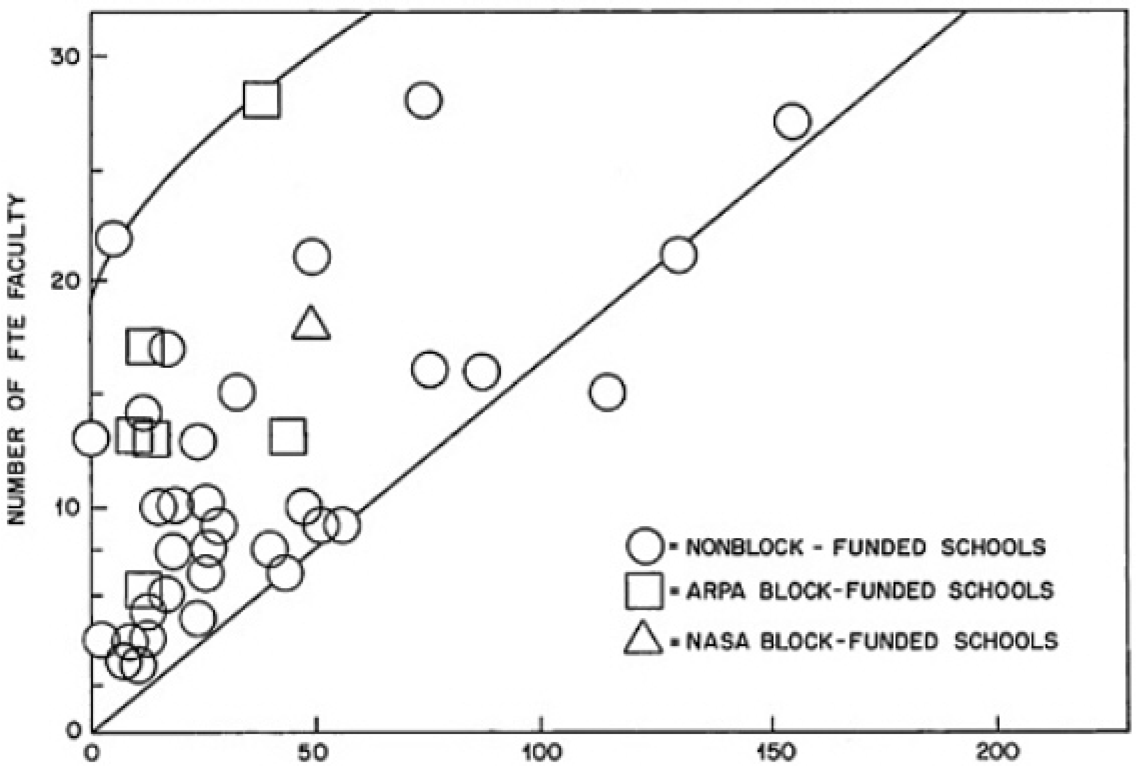

FIG. 7.22 UNDERGRADUATE ENROLLMENTS IN MATERIALS-DESIGNATED DEPARTMENTS (AVERAGE ANNUAL TOTAL OF JUNIORS AND SENIORS FROM 1967 TO 1971)

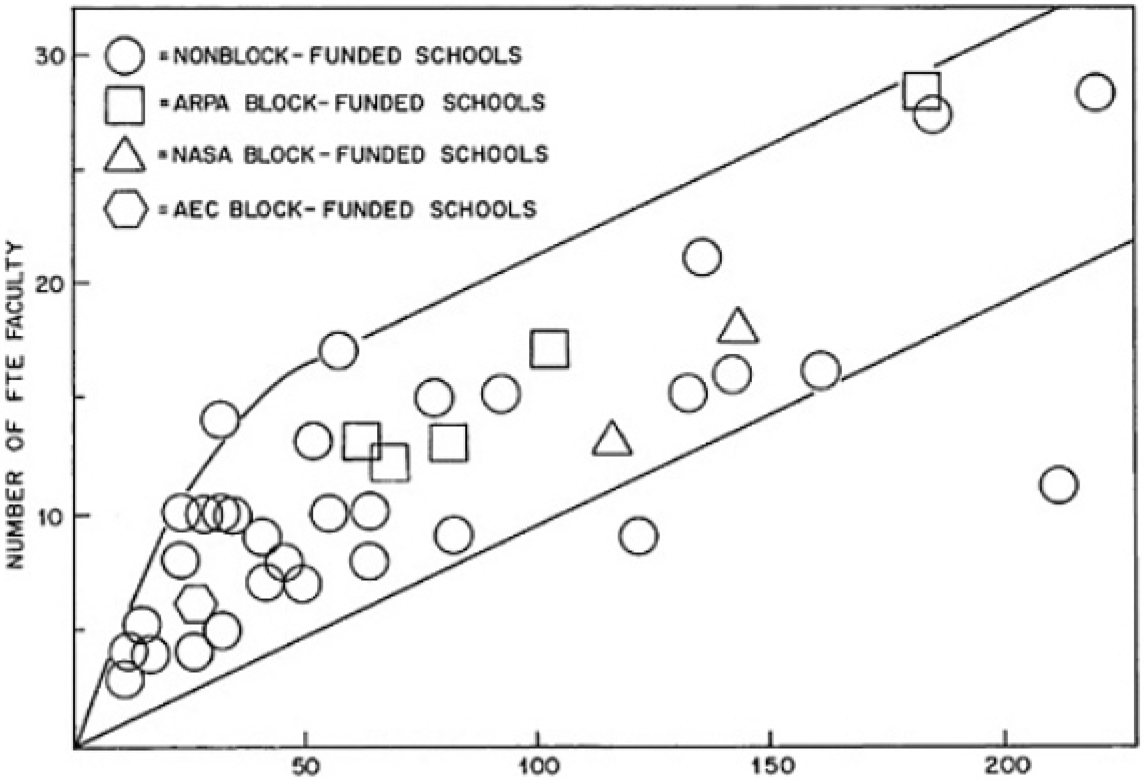

FIG. 7.23 TOTAL STUDENT ENROLLMENT IN MATERIALS-DESIGNATED DEPARTMENTS
(AVERAGE ANNUAL TOTALS OF RESIDENT GRADUATE STUDENTS PLUS JUNIORS AND SENIORS FROM 1967 TO 1971)

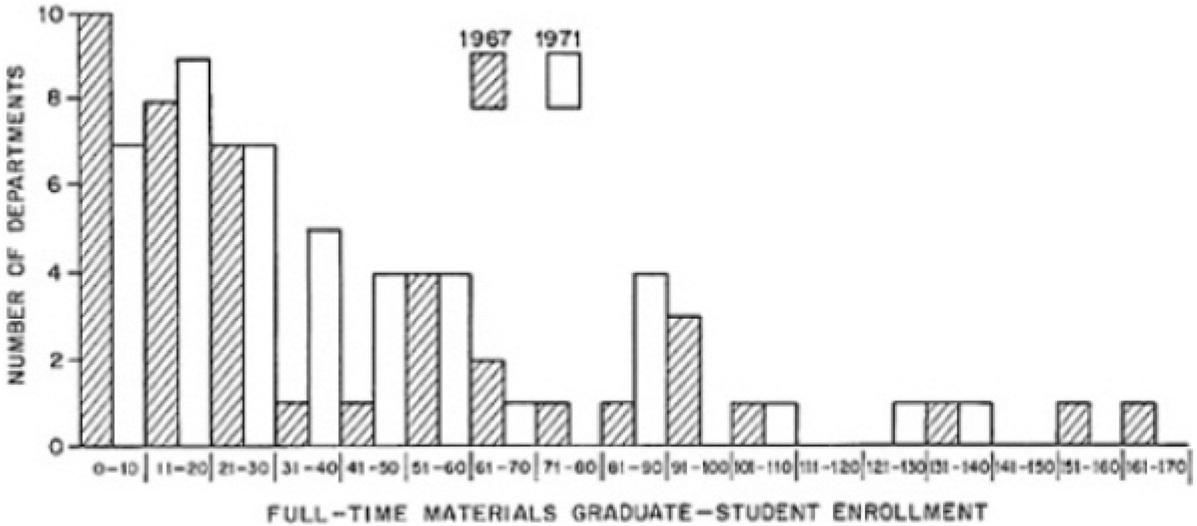

FIG. 7.24(a) SIZE DISTRIBUTION OF GRADUATE MATERIALS-DESIGNATED DEPARTMENTS

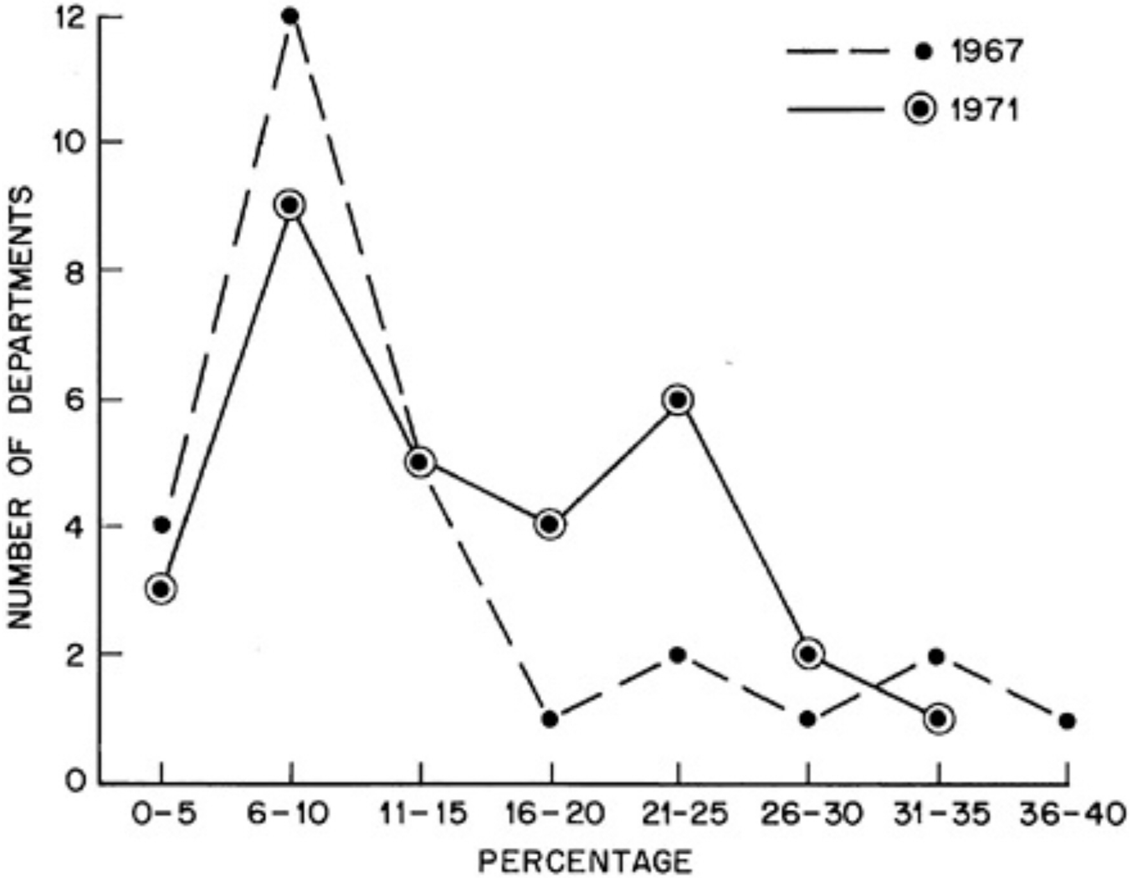

FIG. 7.24(b) FULL-TIME GRADUATE ENROLLMENTS IN MATERIALS DESIGNATED DEPARTMENTS AS PERCENTAGE OF CORRESPONDING ENGINEERING GRADUATE ENROLLMENTS.

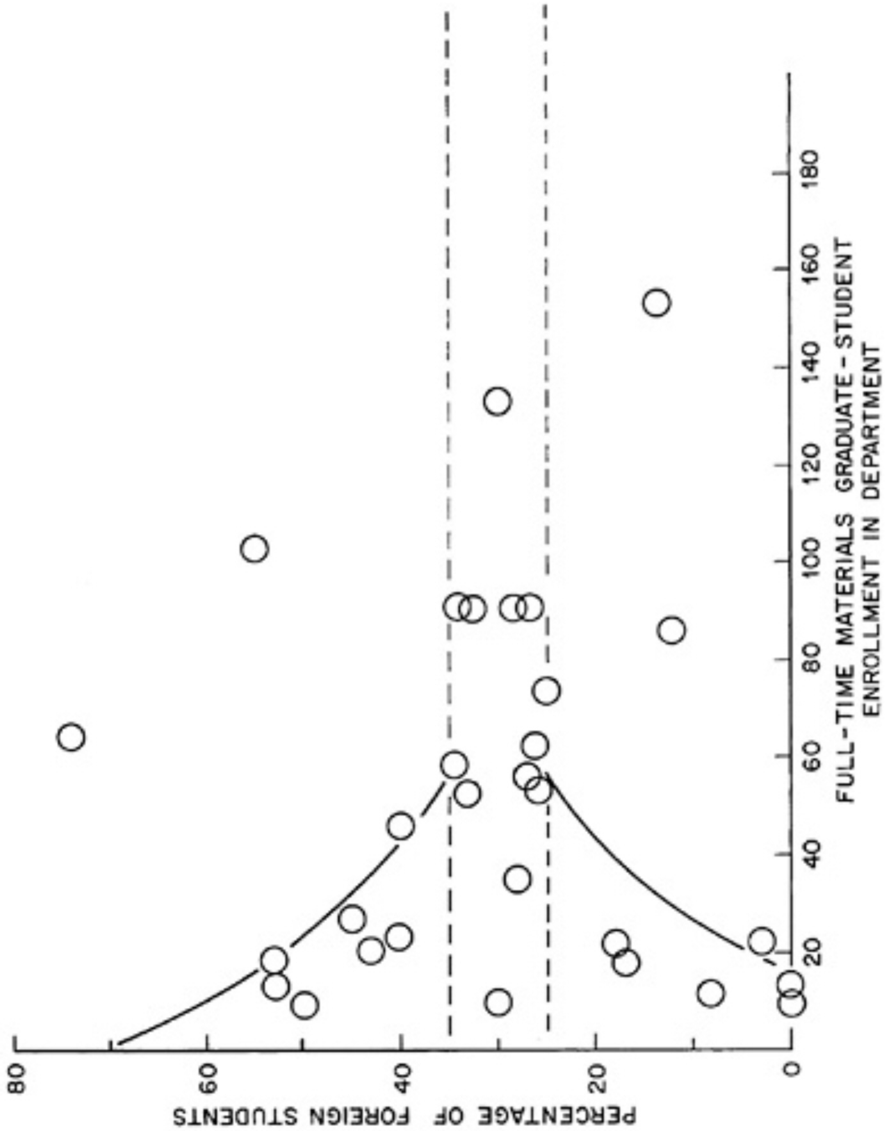

FIG. 7.25 PROPORTION OF FOREIGN FULL-TIME GRADUATE STUDENTS IN MATERIALS-DESIGNATED DEPARTMENTS

TABLE 7.33 Full-Time Graduate Students by Type of Support, 1970

	Fellowship & Traineeship	Research Assistant	Teaching Assistant	Other
All fields (145,970 students)	27.7%	21.4%	24.4%	26.5%
Engineering (31,491 students)	23.8%	30.0%	14.0%	32.3%
Metallurgy and Materials (1,836 students)	20.5%	56.6%	10.5%	12.3%
Physical Sciences (29,522 students)	20.9%	30.6%	36.3%	12.2%

TABLE 7.34 Sources of Federal Support for Full-Time Graduate Students, 1970

		Departments of		Department of					Other U.S. Government
	AEC	Agriculture	DoD	NDEA	NIH	Other	NASA	NSF	
All fields (100%)	5.5%	2.2%	10.6%	9.8%	24.6%	3.3%	4.0%	27.8%	12.2%
Engineering (100%)	6.7%	0.5%	24.3%	6.1%	8.6%	1.7%	8.5%	26.8%	16.8%
Metallurgy and Materials (100%)	21.5%	—	33.8%	4.8%	4.5%	—	5.2%	24.5%	5.8%
Physical Sciences (100%)	13.4%	0.1%	12.3%	7.8%	10.6%	1.0%	5.6%	41.6%	7.8%

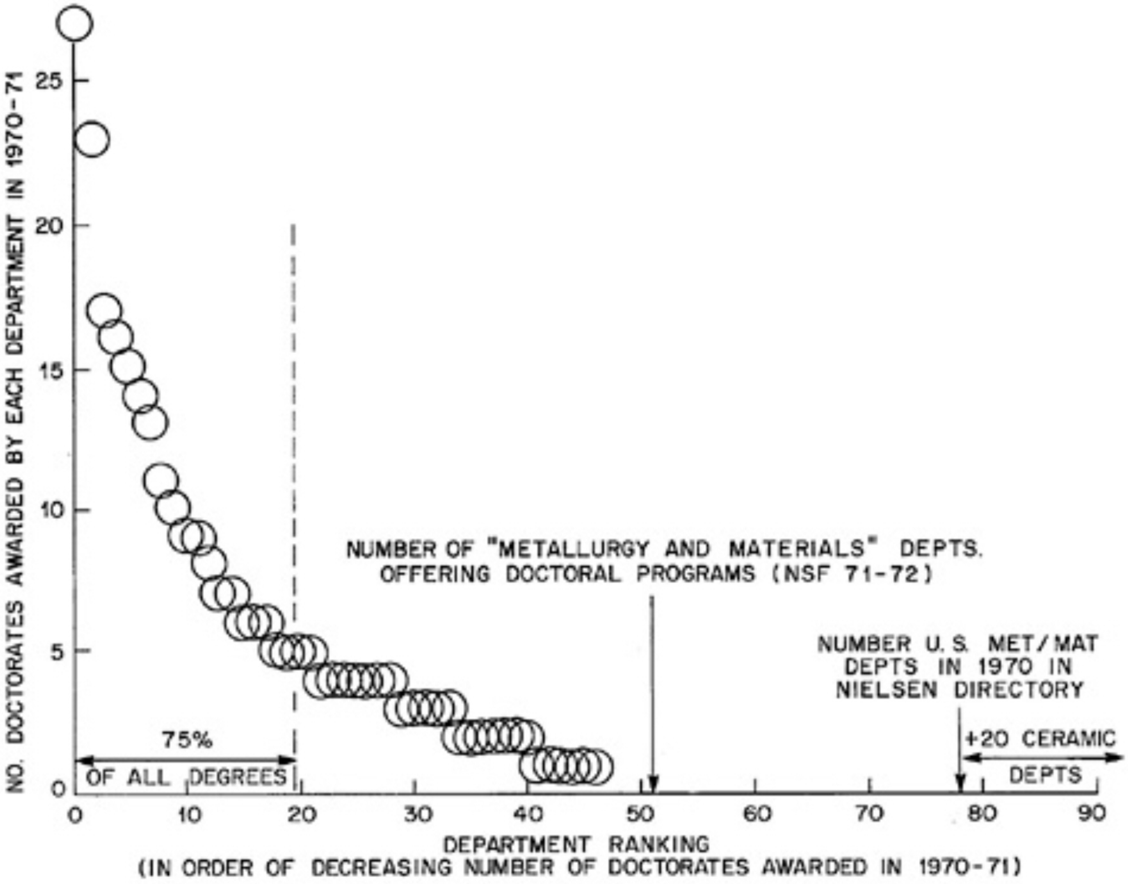

FIG. 7.26 SIZE OF METALLURGY AND MATERIALS DEPARTMENTS BASED ON DOCTORATES AWARDED IN 1970–71.

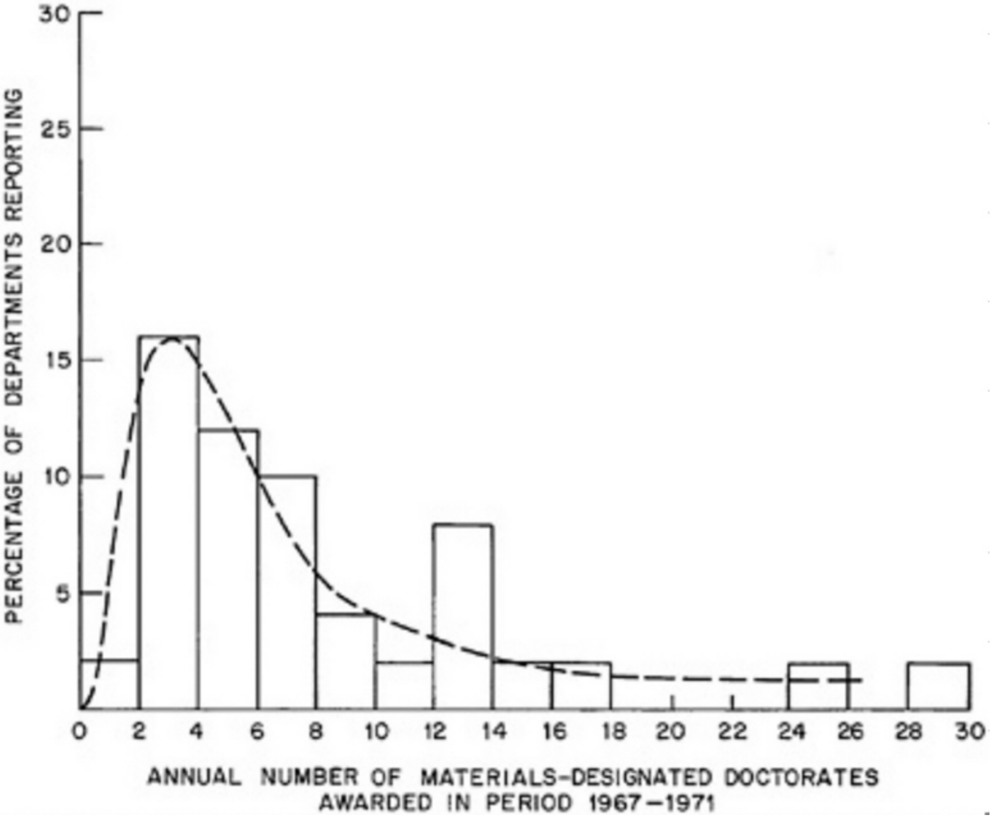

FIG. 7.27 DEPARTMENTAL SIZE DISTRIBUTION BASED ON DOCTORATES AWARDED
NO. OF Ph.D.'s (5 YR.AV.) GRADUATED FROM 50 MATERIALS-DESIGNATED DEPARTMENTS REPORTING ON GRADUATE PROGRAMS
TOTAL (AVERAGE): 270 Ph.D.'s/YR

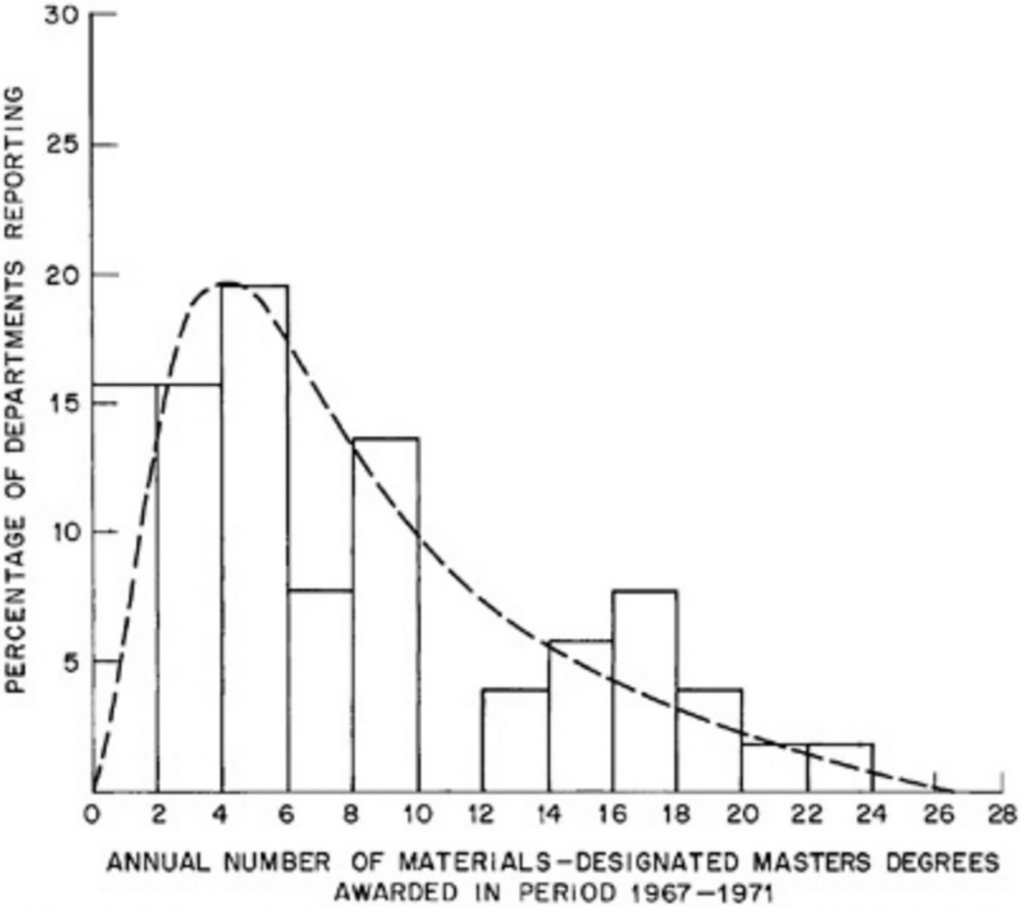

FIG. 7.28 DEPARTMENTAL SIZE DISTRIBUTION BASED ON MASTERS DEGREES AWARDED
NO. OF M.S. DEGREES (5 YR.AV.) GRADUATED FROM 51 SCHOOLS REPORTING ON GRADUATE PROGRAMS
TOTAL (AVERAGE): 354 M.S./YR

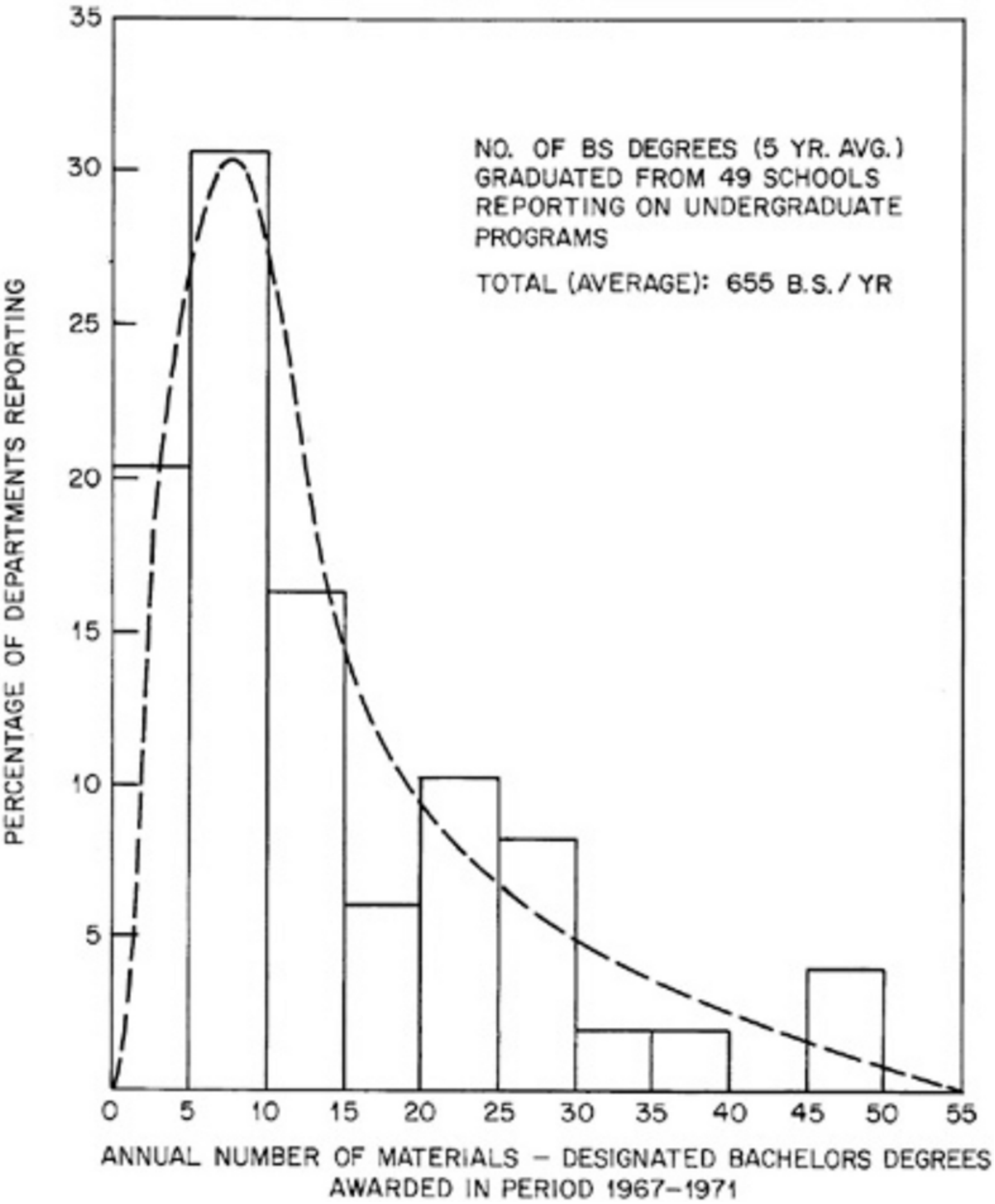

FIG. 7.29 DEPARTMENTAL SIZE DISTRIBUTION BASED ON BACHELORS DEGREES AWARDED

The total numbers of materials-designated degrees are plotted as a function of year in Figure 7.30 (data taken from Radcliffe (1969) and later Engineering Manpower Commission). For comparison, data for all engineering fields are given in Figure 7.31, and the proportion of materials to all engineering degrees in Figure 7.32. The number of bachelors degrees conferred by materials-designated departments has remained at about 2.5% of the total bachelors degrees conferred in all fields of engineering.

The conclusion is clear that the graduate degree output in materials has grown in a manner rather similar to the overall growth in engineering education. There is no evidence in these data for any special increase in materials degree production that reflects the substantial federal block-support of materials centers* during the period since the early 1960's; in fact, the proportion of "materials" Ph.D. degrees has declined relative to those of all engineering fields since the late 1950's—see Figure 7.32.

Curricula in the materials field, whether considered at the graduate or undergraduate level, can scarcely be discussed from a unified point of view. They exist as, and can only be described as, groups of curricula in materials science, materials engineering, in metallurgy, in ceramics, in polymerics, etc.

Table 7.35 lists the number of undergraduate curricula accredited by the Engineers' Council for Professional Development (ECPD) in the materials area. The dichotomy mentioned above can be seen here: It is appropriate to group the "metallurgy and materials" curricula (by name) in a single group (57), and those dealing with ceramics (13) separately. There are no specific undergraduate curricula accredited in the polymer field, but the 19 dealing with mining form a separate group. The universities in which all these curricula exist have been listed in Table 7.29.

The content of undergraduate materials curricula emphasizing metallurgy changed drastically during the 1940's and 1950's. Before that time, emphasis

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* Since the support of these centers is typically concentrated in the materials-designated departments and the physics departments (followed by chemistry), an attempt was made to check whether there was a major increase caused by materials center funding on the output of physics degrees. In the 1971 Survey of Physics, Table 9A in the Appendix to the Bromley Report, it is possible to compute the average increase in physics Ph.D. degrees granted between the two separate periods 1961–65 and 1966–70. One can also separate those universities receiving block funds for support of a materials center (see later for definition) and those not receiving such funds. Inasmuch as the percentage changes tended to be very large in the smaller universities (typically not block funded for materials), only those universities which produced more than 100 Ph.D.'s in 1966–70 were counted. In this group, it is difficult to perceive an increase in physics Ph.D. production caused by the materials-center programs. The block-funded universities increased their physics Ph.D. degrees an average of 50%, whereas the nonblock-funded schools increased 56%. Nevertheless, the advent of block funding undoubtedly spurred the formation of other materials centers and also inspired a new materials focus in the graduate education of many science (and engineering) students whom COSMAT could not specifically identify as "materials majors."

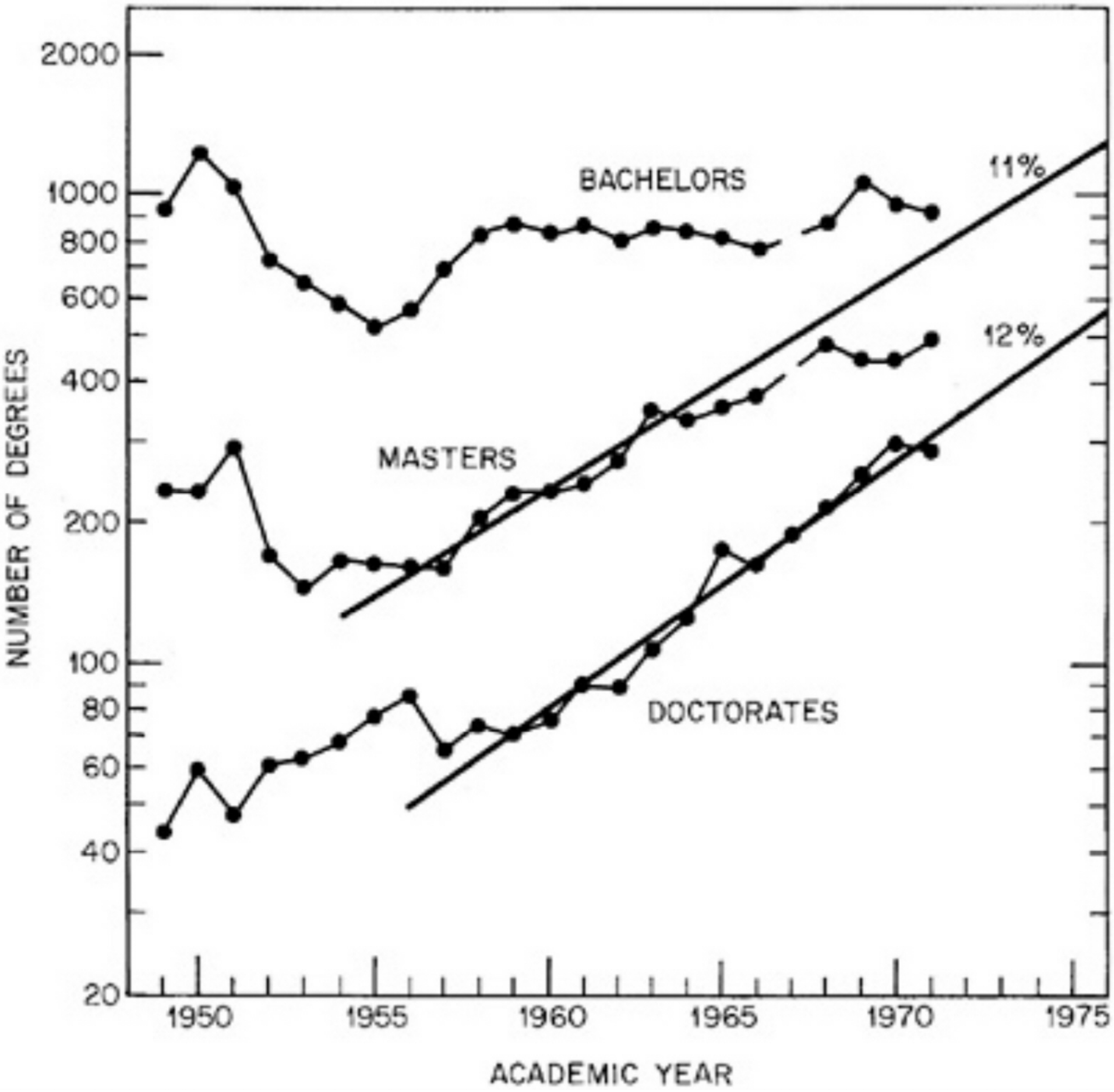

FIG. 7.30 NUMBER OF DEGREES AT VARIOUS LEVELS AWARDED BY MATERIALS-DESIGNATED DEPARTMENTS

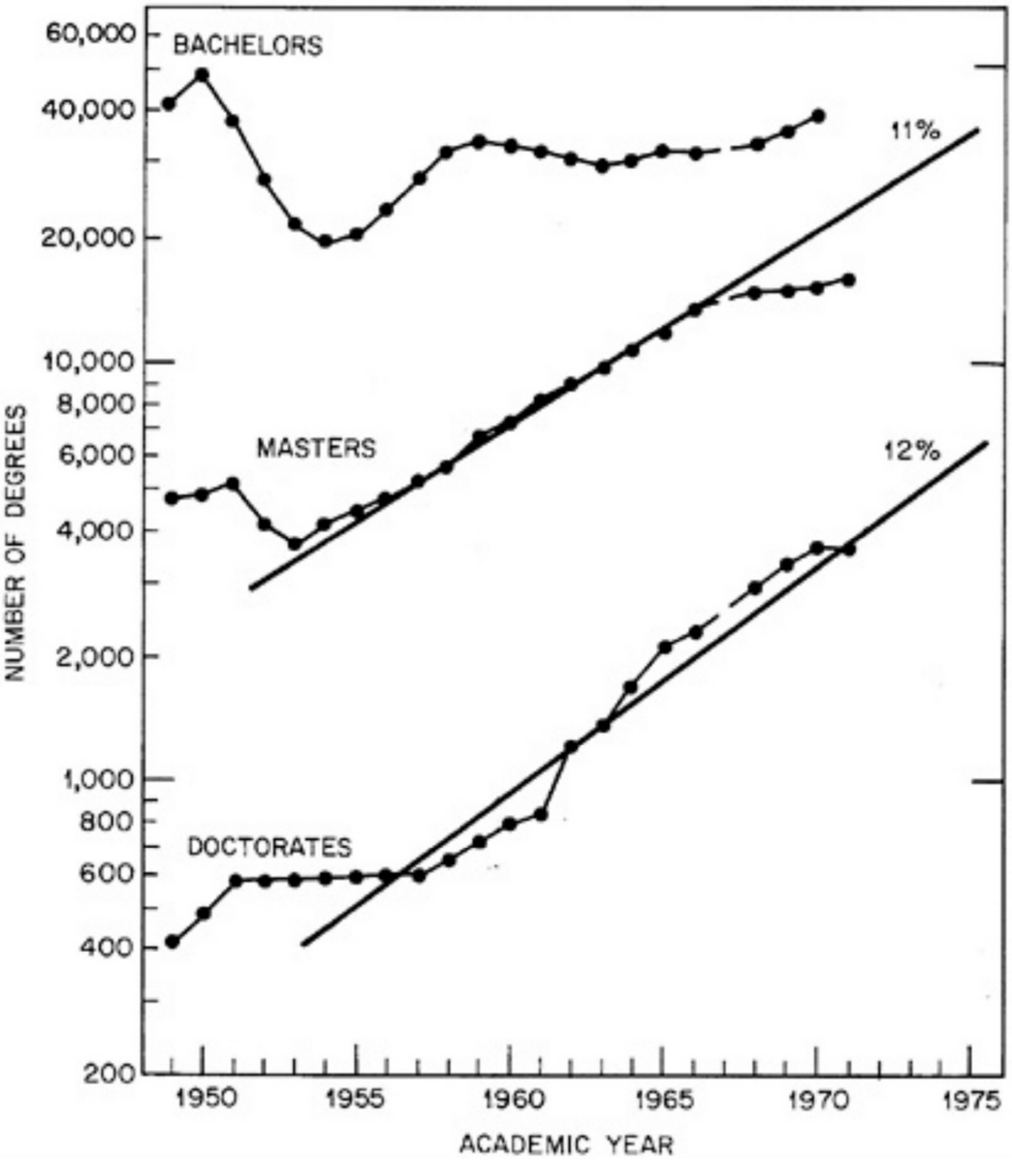

FIG. 7.31 ENGINEERING DEGREES IN ALL FIELDS (US ECPD SCHOOLS)

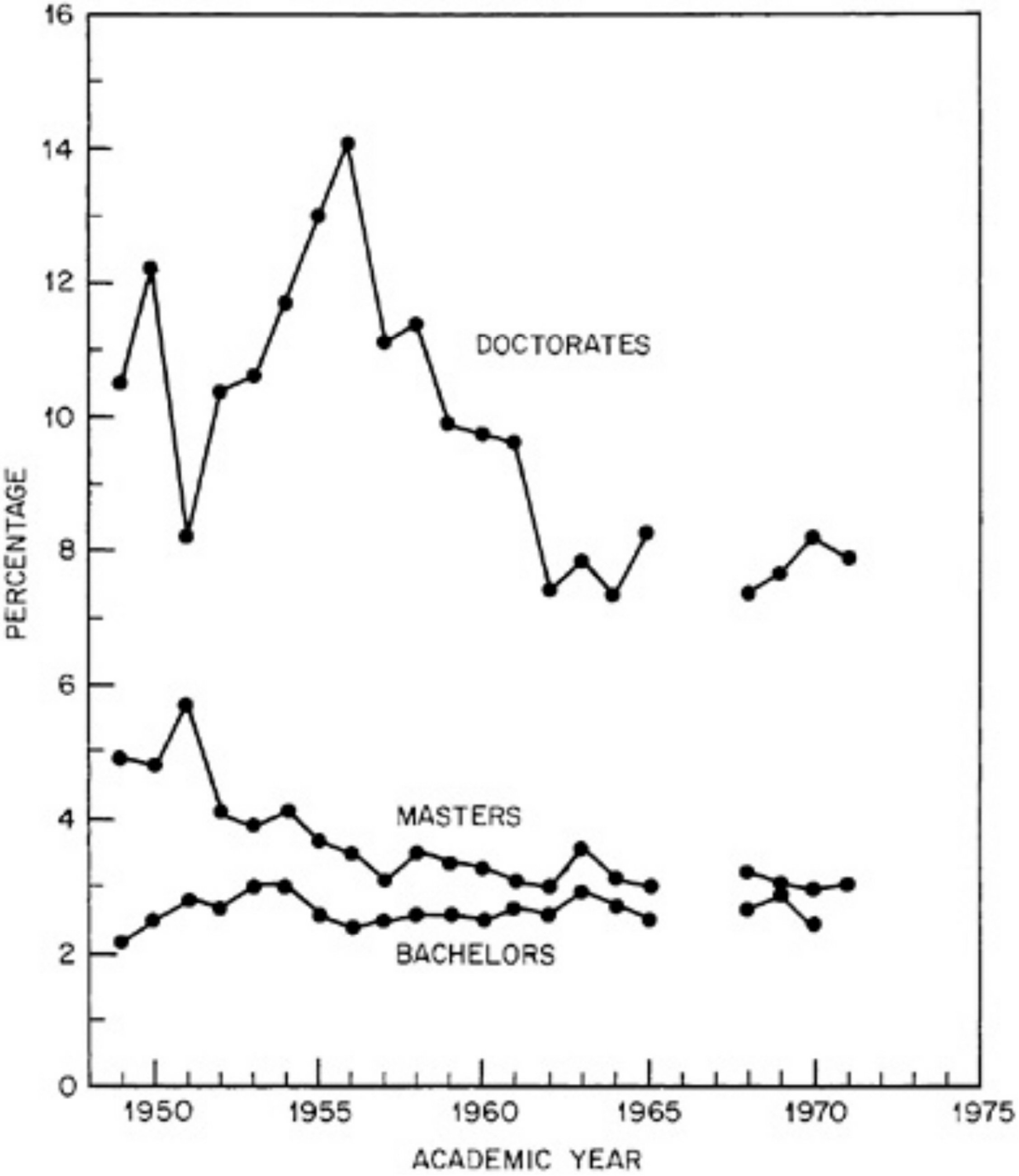

FIG. 7.32 MATERIALS-DESIGNATED DEGREES AS PERCENTAGE OF CORRESPONDING ENGINEERING DEGREES AT ECPD SCHOOLS

TABLE 7.35 Curricula Data from 39th ECPD Annual Report, 1971

The following are the undergraduate curricula accredited in the “materials” area:

Ceramic Engineering	12 (+ 1 option)
Ceramic Science	1
	13
Engineering Materials	— (1 option)
Materials Engineering	4 (+ 1 option)
Materials Science	3 (+ 1 option)
Materials Science and Engineering	3
Materials Science and Metallurgical Engineering	1
Materials Engineering	36
Metallurgy	4
Metallurgy and Materials Science	6
Metals Engineering	– (1 option)
	57*
Mineral Dressing	1
Mineral Engineering	1
Mineral Process Engineering	– (1 option)
Mining Engineering	17
	19

* Some of these curricula appear in the same department.

had been placed on the extraction and processing of metals, and curricula included courses in ore dressing and the production of iron and steel and of nonferrous metals. The faculty of the early departments had a strong background in chemistry, and attention was given to such subjects as corrosion and oxidation. The change in the 1940–1960 period was marked by a strong expansion of the area of physical metallurgy, and later what might be called a generalized science of materials (although still primarily metals) with a dominant theme of structure-property relationships. In some schools, this shift was nearly complete, with only a remnant interest in the processing of materials. In others, little change took place. Elsewhere, and in most cases, a compromise evolved between the old descriptive program and the more quantitative and analytical materials sciences.

Among materials-designated departments, some graduate metallurgy programs have moved far towards incorporating materials science concepts with emphasis on structure-property relationships. At the present time, several graduate curricula in “metallurgy and materials science” are designed to give a working understanding of solid-state physics and its application to real problems in the manipulation of materials. A fairly common pattern has emerged with core courses in phase transformations, defect theory (sometimes restricted to dislocation theory), thermodynamics of solids, mechanics of solids (quite often described as crystal mechanics), the mechanical behavior of real solids, and the electrical, magnetic, and optical properties of solids. Most graduate programs attempt to insure that the student receives a basic education in quantum mechanics, statistical mechanics, band theory, and related theories of solid-state physics. In only a few instances has an equivalent emphasis been placed in the chemical or preparative aspects such as advanced phase equilibria, solid-state reaction kinetics and mechanisms, crystal growth, elemental analysis. This modest influence of chemistry is in sharp contrast to that of solid-state physics.

Over this period of change, several schools developed graduate programs in mineral processing and extractive metallurgy based primarily on chemistry. The curricula include, heterogeneous equilibria, solution thermodynamics, surface chemistry, reaction kinetics, transport processes, and similar subjects, as they apply to the production and refining of materials, particularly metals. In general, graduate research in these areas has found little federal support, in contrast to the encouragement given to research in materials science.

Some specific metal-production research was federally supported as in the case of AEC funding of studies on nuclear materials. Nevertheless, the general outcome over this period has been the discouragement of research and education at most schools in the actual production and refining of materials in favor of an emphasis on structure-property research.

The effects of the emergence of physical metallurgy, ceramic science, and their successor materials science upon the traditional metallurgy curriculum are more variable at the undergraduate level than at the graduate. Some departments oriented toward the terminal B.S. degree have programs with relatively less physical metallurgy and more process and extractive metallurgy, and with a focus on engineering rather than on theory. This pattern appears to have been influenced by a desire on the part of industry to employ B.S. graduates with fairly specific knowledge in metallurgy, ceramics, or polymers rather than the more general exposure to all of these areas that constitute some "materials science" curricula. A few departments offer materials science as electives at the undergraduate level, in the junior and senior years. Most departments have continued with a compromise between an experience-intensive descriptive program and the more quantitative and analytical modern materials science.

The shift from descriptive to analytical curricula in the ceramics field has not gone as far as in metallurgy, inasmuch as the quantitative aspects of physical ceramics are just developing. The same is true of polymerics, the latest of the three materials-disciplines to develop. The departments dealing with polymeric and ceramic materials, moreover, are torn between the alternatives of providing bachelor-level technician-engineers for industry, or introducing more materials science in an advanced-degree program but delaying the availability of the fully qualified graduate accordingly. In the polymer field, it seems clear that a terminal bachelors degree is of limited value, whereas in ceramics this may still be otherwise.

The ten or twelve graduate-degree programs in materials science which are new within the last decade offer an opportunity to discover whether or not a new hybrid "discipline" or unified materials curriculum is emerging. These new curricula have all attempted to restructure the subject matter according to concepts other than the traditional disciplines. Typical sets of subdivisions which have emerged are shown in Figure 7.33.

There appears to be little difficulty in developing a materials science program along patterns similar to those in Figure 7.33, provided that the emphasis is on scientific principles and theory. Questions of the degree to which the individual courses should be applications-oriented rather than basic, and of how the technologies of the different materials should be introduced into the program, are more difficult, and several variations have evolved. Experience shows that it has been easier to design a new materials-science curriculum than to modify an existing one. Frequently such new programs have been able to capitalize on the interdisciplinary nature of the subject matter by using faculty from several departments in a university-wide program.

Some examples of new curricula are described in Appendix 7B. Not all conform to the concepts discussed above. In particular, it appears from a perusal of the curricula in polymer science and engineering that the degree of commonality among metals, ceramics, and polymers is apparently not sufficient to allow an across-the-board treatment of the technology of all three, even in a new program. The covalent carbon-carbon bond dominates the structure-property relationships of polymers to such an extent that major differences between polymers and other materials emerge. Especially at the points in the curriculum where chemistry becomes important, the training needed by a competent polymer scientist-engineer seems to be substantially different from that needed to train scientist-engineers specializing in other materials. To date, possibly because most polymer programs have had a base dominated by chemists and chemical engineers, the materials-oriented polymer degree is the exception rather than the rule.

During the last decade, most engineering schools have considered or implemented an undergraduate survey course in materials as a requirement for all engineers. Various properties, including mechanical, electrical,

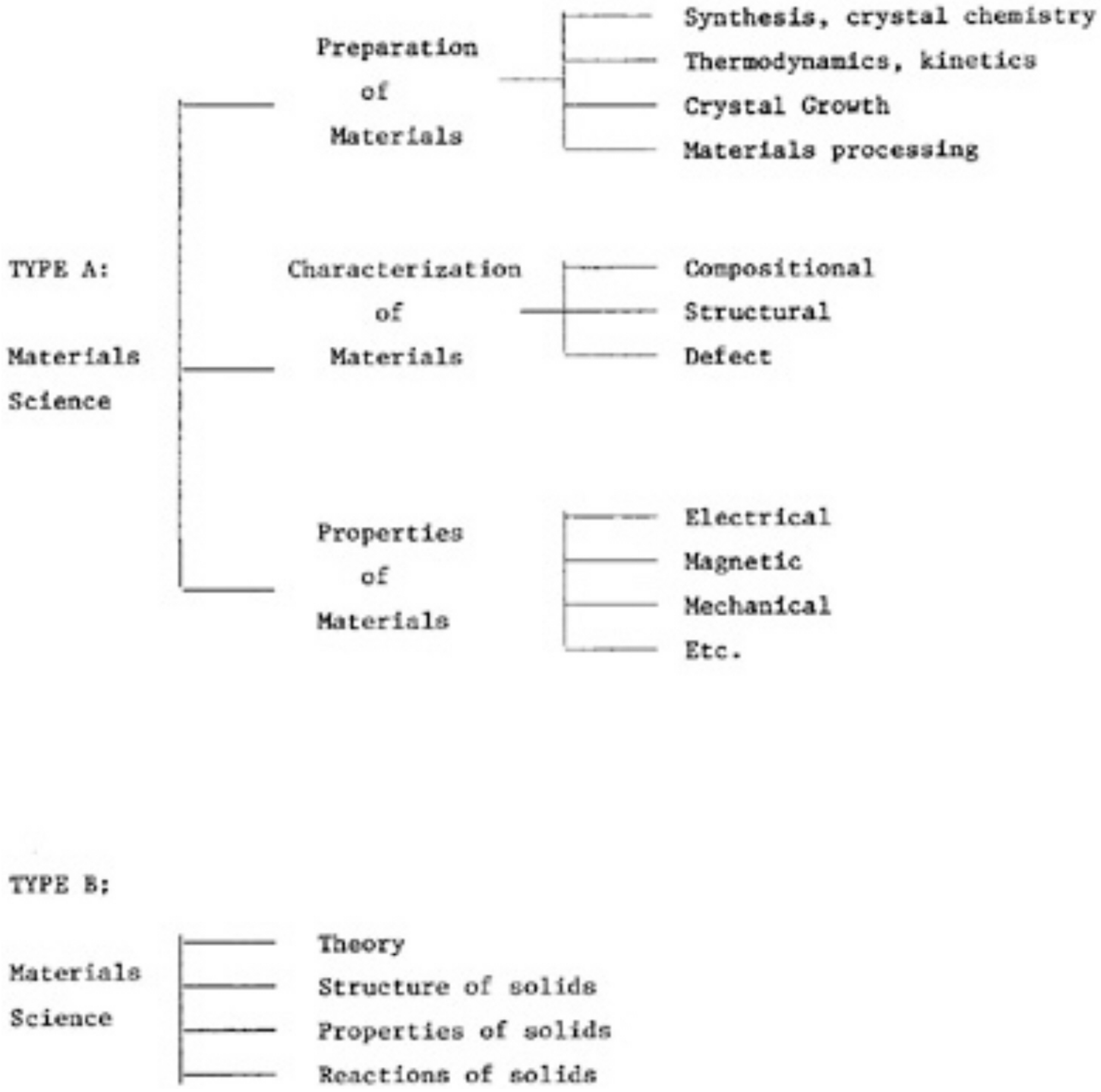

FIGURE 7.33 Alternative Subfields of Materials Science Curricula

magnetic, optical, and chemical, are treated for a variety of materials, with particular emphasis placed on structure-property relationships. Often, a single course is given to students of the various engineering disciplines, rather than separate courses to each. The coverage is usually built predominantly on first-year subjects. Such a course must be limited in depth because of its breadth of subject matter. It is important that this necessary compromise should not isolate the course from the rest of the curriculum, a result which is not easy to achieve. Many schools have begun to regard this initial materials subject as a general materials course, much as the first chemistry subject may be a general chemistry course. The materials relationship to engineering design and practice is also considered significant, although as yet not fully implemented. However, it is remarkable that while most engineering curricula require such a course, virtually none of the science curricula do.

The emerging picture of materials science and engineering is one of an applied, problem-oriented, purposive discipline or cluster of disciplines, especially in comparison with the traditional sciences such as physics or biology. The question inevitably arises whether such a field can be studied adequately within the university, or whether interaction with industry is required. The principal form of such interaction (other than through job placement in materials-producing and consuming industries) appears to be at the undergraduate level in the various cooperative programs However, those associated with materials as such appear to be no more extensive or successful than those in chemical, mechanical, or civil engineering. While it may be that there has been insufficient effort to develop these cooperative programs, it seems more likely that a need for increasing this type of contact has not been expressed by industry.

Probably the most widespread form of communication between engineering schools and industry is through the consulting work of faculty members, and the associated industrial experiences surely influence both course content and mode of teaching. However, there are no reliable statistics to show that the faculty of materials departments are influenced any more in this way than are those of other engineering departments.

A significant question in this review of current materials programs is that of quality. The assessment of the quality in educational matters is an important but highly sensitive undertaking, since there is no simple way of combining the various parameters describing such programs so as to give an indication of general quality. Despite such difficulties, two “peer assessment” (or subjective) analyses of the relative quality of graduate programs in U.S. universities have been made covering the major disciplines in science, engineering, and the humanities (Cartter 1966[14] and Roose and Anderson 1971[15]). Unfortunately, these studies did not include materials-designated programs.

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[14] A.M.Cartter, An Assessment of Quality in Graduate Education, American Council on Education, Washington, D.C., 1966.

[15] K.D.Roose and C.J.Anderson, A Rating of Graduate Programs, American Council on Education, Washington, D.C., 1971.

In an alternative approach to such "peer assessment," the National Science Board[16] analyzed a variety of physical parameters associated with universities and their relation to the quality of graduate programs. More recently, Elton and Rodgers[17] have used similar parameters, and argued for a correlation between the quality of graduate physics departments assessed via these parameters and the ranking arrived at by the Roose-Anderson survey. Similar correlations have been suggested by Elton and Rodgers for other scientific fields. These various analyses point to strong correlations between program "size" and program "quality." Such correlation is in keeping with the obvious difficulties of mounting graduate programs of range and depth with only a small faculty. Likewise, a small student enrollment reduces the opportunities for interactive learning that a large student group offers. Small size also may lead to pressures to convert formal courses to individual study or small-group seminars, which are less demanding on the faculty but often a less exacting experience for the student. However, as is well established, some students find that the individual attention they can receive in a small school can be very conducive to high "quality."

Given the above experience with a wide range of other disciplines, the available relevant data for materials - designated departments have been plotted in terms of the relations among numbers of faculty, doctoral degrees awarded, and graduate-student enrollments. The choice of these size parameters conforms to the methodology of Eldon and Rodgers. The latter approach showed a consistent correlation between the position of a given school on such plots and the Roose-Anderson assessment of graduate-program quality. The resulting plots for the materials departments which are shown in Figures 7.34 and 7.35 do conform to the trend expected by Roose Anderson; if the general relation found for other disciplines holds for the materials field as well, the departments having the higher "strength" of graduate program are those for which the data points lie as indicated in Figures 7.34 and 7.35. These two plots correspond to comparisons of physical inputs (graduate students) and outputs (doctorate degrees). For both figures, it is found that the same 10 departments occupy the upper-strength regions of both diagrams. In alphabetical order, these schools are:

University of California (Berkeley)
Case Western Reserve University
University of Illinois
Lehigh University
Massachusetts Institute of Technology
Northwestern University
Ohio State University
Penn State University
Rensselaer Polytechnic Institute
Stanford University

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[16] National Science Board, Graduate Education, Parameters of Public Policy, Washington, D.C., U.S. Government Printing Office.

[17] C.F.Elton and S.A.Rodgers, "Physics Department Ratings: Another Evaluation," Science 174 (4409) (5 November 1971) 565–568. (Elton and Rodgers have found the Cartter ratings for physics institutions to be essentially supported by objective data.

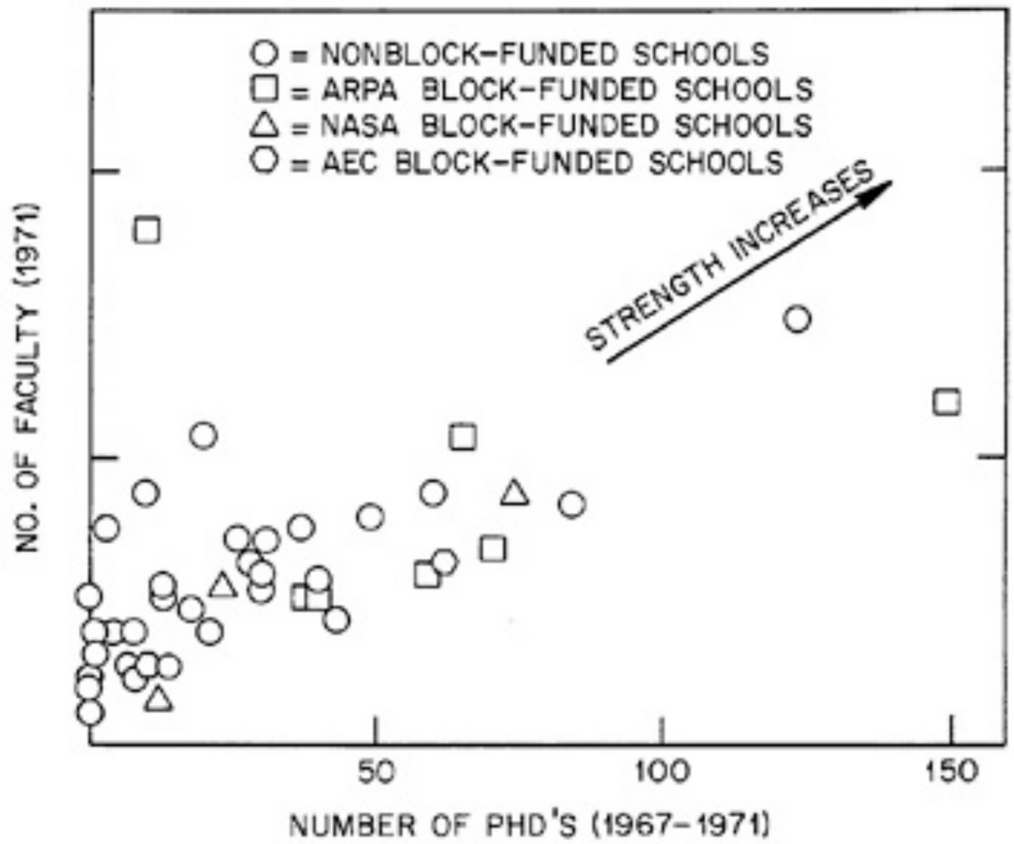

FIG. 7.34 “STRENGTH” OF GRADUATE PROGRAMS OF MATERIALS-DESIGNATED DEPARTMENTS AS INDICATED BY MODIFIED ELTON AND ROGERS APPROACH (SEE TEXT)

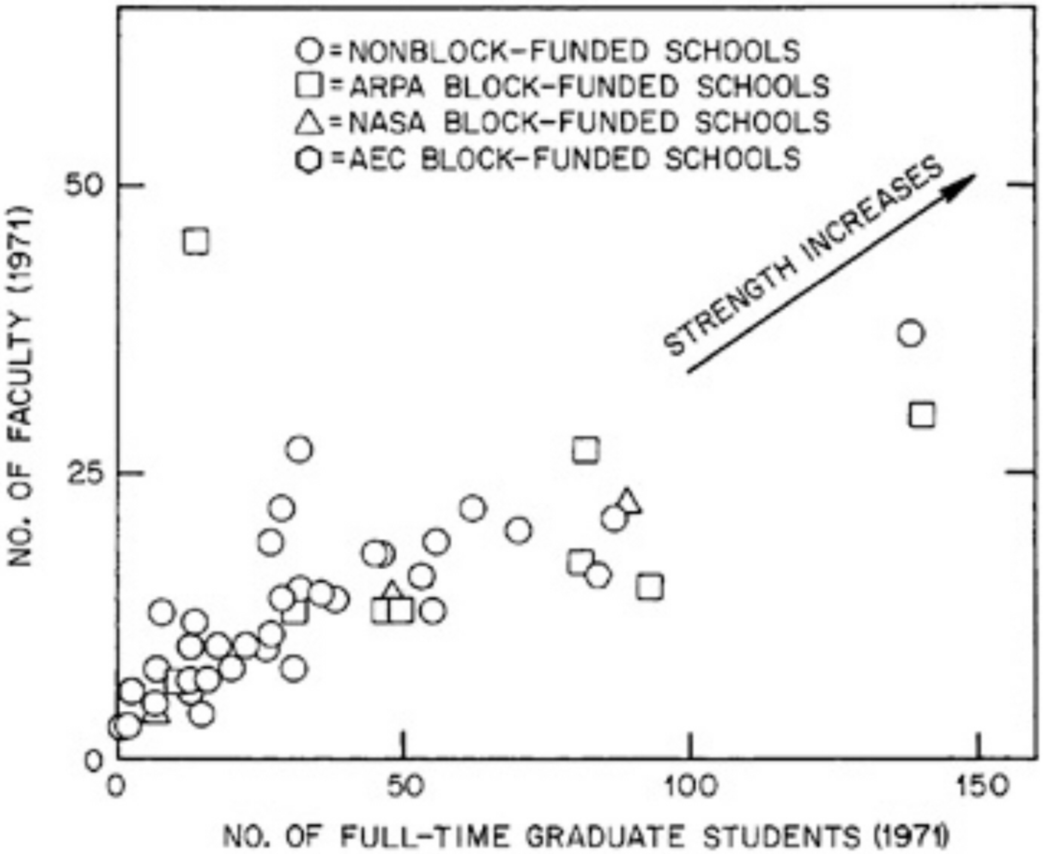

FIG. 7.35 “STRENGTH” OF GRADUATE PROGRAMS OF MATERIALS-DESIGNATED DEPARTMENTS AS INDICATED BY MODIFIED ELTON AND ROGERS APPROACH (SEE TEXT)

Materials-Related Departments

A variety of academic departments in addition to the materials-related ones educate personnel for the materials field. Large organizations, especially research laboratories in high-technology areas, typically utilize a wide spectrum of graduates from university science and engineering departments. While the training in most of these other disciplines has been examined in detail in other studies, it is appropriate here to review the history and trends in their relation to the materials field. In the following, we consider the status of teaching and research in physics, chemistry, electrical engineering, mechanical engineering, civil engineering, and chemical engineering—as the principal materials-related disciplines involved.

Physics: Solid-state physics as an organized subdiscipline really began at the close of the Second World War. The emphasis on solid-state devices and the development of improved semiconductor materials during the War spurred greatly expanded activity in this area. This development was coupled with the push in nuclear physics growing out of the Manhattan Project. University centers like Urbana, Berkeley, and Stanford developed curricula which provided in-depth graduate training in the structure and properties of solids, both from the electronic and physical points of view. At Urbana in 1953, the solid-state physics courses taught by Seitz and Bardeen were jammed with students, with a spectrum of advanced topic courses and seminars being available. Solid-state physics was taught from both a theoretical point of view (electronic-band theory, lattice vibrations, transport theory, etc.) and an experimental one (e.g., Seitz spent two weeks in the first semester discussing methods of crystal growth and purification, strictly from an experimental point of view.). Dislocations and grain boundaries were discussed, although not in great depth. At this time, the body of knowledge centering around the electronic properties of solids was very incomplete, with Seitz' book pointing the general way. Only the simplest of solids, i.e., the alkali metals, and Ge and Si were understood in any detail. The polyvalent metals and particularly transition metals were quite mysterious for the most part. The central thrust of solid-state physics in the 1950's and 60's has been the understanding— both theoretical and experimental—of the properties of pure single-crystal (often elemental) solids. This is not to say that the large body of work that solid-state physicists have done on point defects (vacancies and impurities) has not been significant, but rather that it was peripheral to the main thrust of the field.

Some of the major advances druing this period were:

(a) The development of a reliable band theory of solids and the experimental verification and refinement of these schemes through techniques such as cyclotron resonance, de Haas van Alphen effect, anomalous skin effect, optical absorption, etc. There is now a reasonably detailed understanding of the Fermi surface of a large fraction of the pure metals and the low-lying excited states of the semiconductors and insulators. More recently, physicists have been unravelling the detailed mechanism and strength of electron scattering for states in different parts of the Fermi surface, and are solving the classical problem of the one-electron properties of crystalline solids.

(b) The enormous development of many-body theory starting in the middle 1950's has led to the understanding in considerable detail of many cooperative phenomena, such as superconductivity, superfluidity, and magnetism in the rare earths. This work has been complemented by more phenomenological studies, particularly in magnetism where a truly first-principles understanding of the itinerant ferromagnets is still incomplete.

(c) The understanding of point defects in nonmetals has been likewise developed strongly. Impurity states in semiconductors and ions in insulating crystals have been studied in great detail.

(d) Crystal-lattice vibrations have been understood in a broad class of crystalline solids, thanks to the beautiful techniques of neutron inelastic scattering. A corresponding theoretical understanding of the phonon modes is rapidly coming in, both for insulators and metals. Other collective excitations such as plasmons and magnons are also well understood in many substances.

No doubt many other areas, including device development such as transistors, lasers, Gunn devices, etc., could be listed. However, these are being pursued largely in electrical engineering departments.

The important fact is that the research advances described above have been incorporated into the solid-state graduate curriculum in considerable detail, and a well-trained solid-state scientist is expected to know a major fraction of this work in depth. Advanced seminars on special topics is the norm in solid-state programs, and this contact with the forefront of knowledge in this area has been particularly helpful to the graduate students in physics, and in other disciplines as well.

A propensity of physicists is to study a phenomenon in microscopic detail to understand what is "really going on." One typically starts with a simple case, then generalizes to more complex situations. This pattern has led to emphasis on simple, pure, crystalline solids. Solid-state physics has largely completed this phase of development, and is now evolving into a more mature discipline by reaching out to neighboring fields for new problems. This is not in any sense a revolution, but rather an evolution of the interests and capabilities of a fraction of scientists in the field. Examples of the recent trends toward more complex systems are:

(a) A large activity by some prominent people in alloy science, both dilute alloys (nonmagnetic and magnetic) and concentrated alloys, has led to the understanding of the electronic structure of impurities in metals (i.e., virtual levels, localized moments, etc.) and after many years of work to the discovery of schemes which allow one to investigate theoretically concentrated alloys in a realistic manner (the coherent-potential approximation).

(b) The amorphous solid is under vigorous attack by theorists, and experiments with exciting new results are coming in rapidly. The thinking in this area bridges the gap between the chemist's covalent bond and the traditional band scheme of the periodic solid. Based on these and related advances in band theory, alloy physics, and lattice dynamics, further progress on the problem of bands in solids in general will emerge.

(c) Surface science has long been pursued by a small group in physics. However, several years ago a significant break came when a number of outstanding scientists in solid-state physics turned their attention to the structure and properties of clean surfaces, and the interaction of surface with adsorbed atoms and molecules. This field is growing rapidly, and its impact on problems of surface bonding, corrosion, oxidation, catalysis, fatigue and fracture, etc., is likely to be enormous. There is an expanding group of solid-state people knowledgeable about the practical materials aspects of these problems, and there is a sense of excitement about getting involved in the fundamental understanding of these "messy" areas.

It is apparent that solid-state, physics has matured to a point where it is capable of making significant contributions to fields which heretofore have been just too complicated to handle in a microscopic way. For any real measure of success, a truly interdisciplinary approach is required. What is needed is a strong collaboration between the traditional materials science and engineering groups and the solid-state physics community in specific areas such as alloys, glasses, surface phenomena, and fracture. Longstanding biases have tended to separate the groups because of alleged "blue sky science" versus "dirty plumbing" being all that the "other" group is capable of handling. Leadership by the most creative and distinguished members of each community is clearly necessary to bridge the gap, and one may expect that the present contacts will be rapidly strengthened in the future. It is important to present jointly sponsored courses which cover topics involving materials science and engineering, solid-state physics, and chemistry, in which students and faculty from these disciplines work together and learn each other's language, problems, and capabilities. Modest steps in this direction are being taken at a number of institutions. This approach is an important adjunct to, rather than replacement for, the traditional discipline-oriented teaching and research in the universities.

Chemistry: Education in materials science per se has been typically treated with "benign neglect" by chemistry departments, except in a few cases where such departments have provided a home base for polymer programs. This is true in spite of the fact that, historically, instruction in each of the three major categories of materials (metals, ceramics, and polymers) often began as a subdiscipline of chemistry. The polymer curricula have developed last, and where they exist at all, are still closely allied to chemistry departments, with three or four major exceptions.

The contribution of chemistry to materials education comes partly in the content of the basic courses. The study of materials rests on such fundamental subjects taught in chemistry departments as chemical bonding, thermodynamics, kinetics, compositional analysis, and the snythesis and properties of organic and inorganic compounds. Much of what was taught as physics a generation ago is now firmly established as chemistry, including major parts of physical chemistry and almost all of instrumental analysis, now an integral part of MSE training.

The specific study of the different classes of materials (metals, ceramics, polymers) in a typical chemistry department is usually implemented by inclusion of such subject matter in core courses, and only rarely by having a separate course in any one of these categories. The amount of such content included varies tremendously from one school to another, but in the vast majority, it is rather modest. Discussion of metals will typically be limited to a description of metallic bonding in general chemistry; the analysis for metals, free or combined, in courses in analytical chemistry; and discussion of metal compounds in inorganic chemistry. Ceramics substances receive even less attention. A modern course in general chemistry may spend a day or so on the glassy state (as exhibited by both organic and inorganic materials), but otherwise very little is likely to be said about ceramic materials, even those as important as cement, mullite (the principal component of all whiteware and pottery), or modern electronic materials. Similarly, polymers are scarcely treated, though opportunities to introduce the subject matter are plentiful.

Electrical Engineering: A few years prior to the advent of the transistor, many electrical engineering departments shied away from materials. This attitude was probably generated by the fact that the materials aspects of electrical components and systems had reached a certain state of maturity. The emphasis was on terminal behavior of devices combined with some insight into the components to the extent that they affected the terminal properties. A small sector of the electrical engineering academic community, however, remained conversant with the materials aspect of electrical, magnetic, and electronic components. This was particularly true in those electrical engineering departments whose emphasis was more on electronics than on power.

At the undergraduate level, electrical students sometimes took a materials course, usually offered to students in the engineering school, taught in the department of metallurgy (and/or materials science) in those universities which had such a department. The course, generally at the junior level, presented the basic principles of the internal structures of materials aiming at an understanding of structure/property relationships. The course typically started with a qualitative description of mechanical, thermal, chemical, electrical, and optical properties of materials. It then moved to an elementary treatment of atomic bonding, which complemented previous understanding obtained in physics and chemistry courses, and then a treatment of molecular, crystal, and noncrystalline structures. The subject of imperfections would be given some consideration. Electronic processes in materials with emphasis on electric and magnetic behavior were studied in some detail, while still at a rather elementary level. When the course was taught by a metallurgist, metallic phases and their properties were covered in some detail. If not, after a cursory treatment, the course moved on to ceramic and, perhaps, organic materials. In the more elaborate courses, particularly when they were two-semester offerings, multiphase materials and equilibrium relations were studied, as well as phase reactions and the stability of materials in various environments.

The advent of the transistor and the emergence of solid-state electronics as an important branch of technology not only introduced dramatic changes in electrical engineering as a discipline, but also influenced the curricula of electrical engineering departments. The outcome of the changes was the addition of new courses concentrating on electronic processes in materials and containing the following topics: structure of crystals, quantum mechanics, atomic bonding, statistical mechanics, free-electron theory, semiconductor theory, semiconductor materials, and introduction to semiconductor devices. Some attention was given to electron emission, dielectric processes, magnetic and optical processes. This course served as an introduction to physical electronics, the emphasis of which was essentially semiconductor phenomena and devices, and was to be followed by courses in electronic circuits.

All the courses mentioned above were actually required in most electrical engineering (EE) departments until the late 1960’s. Somewhat earlier many such departments recognized the need to incorporate computer courses into the curriculum. In fact, pressures from many sectors suggested the introduction of at least one hardware-oriented course besides the one on computer programming offered at the freshman or sophomore level. In many instances, the new computer courses were given as electives, a development that frequently compelled the offerings in materials to become electives, too. At present, while physical electronics is still required in many EE departments, the preceding courses (i.e. materials science and/or electronic processes in materials) are becoming elective. In some EE departments, students still take a sophomore elective in materials taught jointly by several instructors. However, the semiconductor field has come of age, and the availability of integrated circuits is forcing systems design at a different level, while helping deemphasize the importance of the individual device, if not the materials aspects. If semiconductors are losing prominence in the field, materials at large are regaining attention. The thrust toward more relevance in the curriculum coupled with a new emphasis in interdisciplinary programs, even at the undergraduate level, may be providing impetus for a broader materials offering in EE departments.

At the graduate level in most EE departments, students are usually not required to take any specific courses in materials. Those interested in semiconductors usually take one or two graduate courses in quantum mechanics in the physics department, followed by one or two semesters of solid-state physics, and then at least two EE courses in solid-state devices and one in integrated circuits. Other courses with a materials orientation depend a great deal on the particular emphases and strengths of the EE research programs. It is not unusual to find combined offerings in thin films, magnetic phenomena, materials, and devices. In EE departments at universities which have good materials science departments and/or interdisciplinary programs in materials, students may take a variety of specialized courses on materials from the respective departments.

Many EE departments engage in materials research. Some of these departments may not have the standard EE title but rather electrical sciences, electrophysics, etc. However, their faculty members publish in journals and participate in meetings that are a part of the EE community.

Typical designations of the research efforts related to materials are: materials, with emphasis on electronic phenomena and devices; solid-state electronics, where the effort is usually more concentrated on phenomena and devices than on the materials per se; magnetics, with only minor emphasis on materials; electrophysics; applied quantum mechanics. In the latter two areas, work is usually done which utilizes some materials as vehicles for the investigation of physical phenomena.

The materials most commonly utilized for electronic and device studies in EE departments have been the major semiconductor families: silicon and germanium, III–V and II–VI semiconducting compounds. Integrated circuits with silicon and gallium arsenide as base materials have provided topics for a few groups to conduct research with some materials orientation. However, most of the research and/or development work on the latter subjects, which is mainly of a processing nature, has taken place in industrial laboratories.

In recent years, some EE departments have become active in research on optical materials. Most research efforts on optical integrated circuits are spent at present on searching for materials of good optical properties (such as low-loss materials for optical waveguides, etc.). So far, the materials that have been studied include ZnO, ZnS, Ta_2O_5, sputtered glass, polyester epoxy, and organic polymers. Another area of endeavor is connected with electro-optic materials for nonlinear optics and parametric devices. At present, the best known electro-optic materials are $LiNbO_3$, $LiTaO_3$, $Ba_2NaNb_5O_{15}$, KD*P, $PbMoO_4$, and ZnO. Such materials are essential for various kinds of optoelectronics (nonlinear optics, parametric devices, and modulators for laser communication).

A third area of research on optical materials is connected with large-scale displays and/or holographic displays. Photopolymers, photochromic materials, liquid crystals, magnetic thin films of MnBi, thermoplastics, and electro-optic crystals are the most useful optical materials in this field.

Mechanical Engineering: In recent years, mechanical engineers have become more and more involved with materials and their behavior in the design, construction, and use of many devices. A few years ago, it was sufficient to consider materials to be homogeneous and to design with relatively simple stress analysis based on the theory of elasticity. Today the mechanical engineer must be almost as familiar as the metallurgist with modern theories of bonding, microstructure, and the important role of defects. This is, in part, due to the advance in design requirements relative to stresses and temperatures to be carried by structural members. It is also due to more advanced processing procedures that have resulted from competition in performance and manufacturing costs. The kinds of materials available to the engineer have increased enormously since World War II. Where a few simple structural and tool steels were previously on hand, the modern mechanical engineer utilizes a variety of alloy steels, carbides, and oxides, and a whole host of nonferrous materials including titanium alloys and refractory materials. The modern mechanical engineer has also had to carry his design well into the plastic regime and to take into account the inherent dispersion in performance of relatively brittle materials.

Two major design requirements have become particularly important to recent graduates in mechanical engineering; structural reliability and long service life. Thus, mechanical engineers have to be knowledgeable in the areas of fatigue-life estimation and flaw sensitivity of materials. These materials questions have become critical because of contractual responsibilities for safe structures with much higher performance requirements. The mechanical engineer must not only understand such materials properties as strength, fracture toughness, fatigue and creep resistance, wear and corrosion of changing alloys, but he must also be able to assess the use of a broad range of materials.

The jet engine, virtually unknown in this country in 1946, has made it necessary for design and manufacturing engineers to adopt an entirely new approach to materials. The continuing demand of engine designers for more heat-resistant materials so that operating temperatures and hence efficiency can be increased has been met by metallurgists and materials engineers. However, the newer materials are much more difficult to cast, forge, and machine, and they have introduced some very difficult challenges for mechanical engineers who are involved with production.

The development of the nuclear-power industry has led to several unique materials problems for mechanical engineers. The design requirements include fail-safe and safe-life assessments for constructional alloys under conditions of irradiation, multiaxial stress states, elastoplastic deformation, creep, and nonlinear fracture mechanics. One of the major design deficiencies is turning out to be a lack of suitable data on the material response to complicated loading and history.

Aerospace structural requirements have also become more stringent as greater performance is demanded. Material selection has changed from a few basic aluminum alloys to many new aluminum alloys, titanium alloys, very high-strength steels, and composite materials including the new advanced boron- and graphite-fiber reinforced epoxy materials. A whole new technology is being developed for the composite materials, with mechanical engineers and materials engineers working to create optimally useful forms of composite materials for advanced structures.

Civil Engineering: In principle, civil engineers are deeply involved in the engineering of large-scale materials systems. However, the materials in question are not being subjected to much basic research. These materials seem to be of interest mainly to civil engineers and are of quite low cost, in the cents-per-pound range, and include sand, rock, cement, bituminous concrete, tar, asphalt, steel, aluminum, fiberglass, epoxies, polyesters, glass block, glass foam, paper-rag felts, etc. The civil engineer is required to specify the materials to be used in many structures such as bridges, pavements, buildings, and industrial equipment. Often, however, he is inadequately trained for this task. In fact, most degree programs in civil engineering do not interface well with materials departments. The maximum interaction tends to occur where there are interdisciplinary materials-oriented research programs involving systems of importance in civil engineering.

Research in civil-engineering material groups over the past years has not been very fundamental in nature. There was a period in the mid-1960’s when some departments were beginning to do more basic research on materials of construction, motivated by the availability of NSF grants. A few civil engineering departments now have cement chemists or soil scientists who have been studying the basic properties of these materials.

Understandably, most of the materials research in civil engineering departments is application-oriented; that is, there exists a problem and the research is directed toward solving this problem. Some investigations of this type are carried out through cooperative highway research programs. However, the amount of basic research done on materials for construction is very small throughout the civil engineering departments of the U.S. Moreover, there is no indication that this pattern will change in the foreseeable future because (a) the time devoted in civil engineering curricula to materials is quite small; only one or two courses are typically devoted to materials and the science of materials at the undergraduate level, and (b) there seems to be a shortage of qualified personnel to teach civil engineering materials subjects in a modern way and to carry out the corresponding research.

Chemical Engineering: Since materials can be regarded as chemicals, and chemical engineering is a discipline that applies the science of chemistry to the problems of society, it is not surprising that chemical engineers and chemical engineering education have had a long association with materials. On the other hand, few would say that the chemical engineering curriculum is strong in the subject. Some perspective on this point can be gained through a discussion of specific areas.

One of the first courses to become established in the undergraduate chemical engineering curriculum was often called strength of materials. Another subject widely required until about 15 years ago was related to some aspect of metallurgy. Yet, very few chemical engineers have become involved with the design of structures from the standpoint of mechanical strength, or with the processing of ores to the refined metal. These courses were regarded as part of the chemical engineer's general background, but such content has been steadily decreasing.

Two other areas related to materials became of primary concern to chemical engineers. The first was corrosion, undoubtedly because of its role in equipment failures during the growth of the chemical process industry before World War II. Instruction in corrosion was typically covered in a course on both corrosion and electrochemical processes, perhaps in a course concerned with chemical plant design, or in one related to metallurgy. By building on the electrochemistry content of physical chemistry, the treatment of corrosion could be made relatively quantitative. The second materials area developed in the chemical engineering curriculum could be identified by the title of a text published in 1942; namely, Industrial Chemistry of Colloidal and Amorphous Materials. At first, this type of course covered such natural materials as leather, rubber, paper, and textiles. Later, the development of the synthetic organic chemical industry led to the production of the more complex molecules, such as polymers. However, while polymers have been growing in industry, chemical engineering departments have decreased or eliminated their courses in industrial chemistry where coverage of polymeric materials might occur. A widely read document relating to accreditation of chemical engineering curricula states that instruction in materials from the point of view of the physics and chemistry of the solid state is desirable. Many schools satisfy this requirement with a one-semester course containing the word "material(s)" in the title, but others rely on the materials content of the chemistry courses and such topics as corrosion and strength of materials which are covered elsewhere.

The opportunity for specialization at the graduate level has permitted many students and faculty in chemical engineering departments to concentrate in the materials field. Those schools that built materials research laboratories in recent years have usually attracted one or two collaborators from the chemical engineering department, particularly in the area of polymeric materials. Polymerization kinetics and other problems related to polymer synthesis and manufacture are also attractive fields of research in chemical engineering. Polymer processing and catalytic materials have been of major interest to chemical engineers, but most of the important developments here have occurred in industry rather than at the universities. Recently, the relationship between catalytic activity and crystal structure of the catalyst has been demonstrated for some systems, and research along these lines is enjoying increased attention. Similarly, porous solid adsorbents that have high selectivity for certain materials owing to their surface structure are being developed. Another new material being studied in some chemical engineering laboratories is the porous film used in reverse osmosis. Materials handling is being investigated by some chemical engineers in the collection of particulate solids and the separation of solids by various means. Problems in corrosion are also under study at a few locations.

Where graduate-student and faculty interest in materials exist, one or two graduate courses related to materials are frequently offered by the chemical engineering department.

Some Comparisons of Materials-Related Departments: There is rather wide agreement that physics departments have played an important role in the development of materials science, while chemistry departments appear to have been less directly involved. Similarly electrical engineering is generally held to have been much closer to the recent advances in materials than mechanical engineering has been. Nevertheless, it is difficult to describe, quantitatively, the various materials activities in the traditional disciplinary units. Obviously, a part (solid-state physics) of the activity of a physics department is likewise part of MSE; the same can be said for polymer programs in chemical engineering or chemistry departments. Through a questionnaire, an attempt has been made to obtain comparable data on the extent of materials activities in all the materials-related departments. A number of such departments were asked for their own evaluation of their involvement in materials science and engineering in answer to the following two questions:

> What percentage of your faculty/student and research effort has been concerned with problems which are relevant to the scientific understanding of materials? __________%
>
> What percentage of your students would qualify, in your opinion, to be considered as materials scientists or materials engineers? This percentage could be estimated on the basis of the following parameters: __________%

Extent to which courses offered and taken might especially qualify a student for research in the field of materials.

Extent to which the thesis topic is concerned with materials.

Extent to which the first job (where known) is in materials education or research.

The resulting data plotted in Figure 7.36 offer some picture of the “materials-relatedness” of various disciplines. The findings for chemistry are surprising, and may reflect some misunderstanding of the terms used in the questionnaire. For example, a few chemistry departments claiming no contact with their own materials centers reported that 100% of their work was in materials.

Materials Research in the Universities

Magnitude of Materials Research Effort

The overall distribution of the federal R&D support at universities is shown in Table 7.36. (Such support comprises more than 90% of the funding for materials research in the universities.) From this table, $17.6 million goes directly to the materials-designated departments, but the data do not identify how much of the support to other science and engineering disciplines is devoted to materials research. The significant magnitude of the latter is shown in Figure 7.37, which presents available data from various sources for the different categories that make up the total materials research effort at U.S. universities. The figures from the COSMAT questionnaires have provided the most detailed picture of this materials research funding. The findings from the different sources are reasonably self-consistent with the exception of the discrepancies between columns (a) and (d). These discrepancies appear to arise from the fact that the COSMAT data include support from university, state, and industrial sources, and that slightly different definitions were used by the ICM.* The COSMAT data (column (d)) are more precise than any available previously up to the $68.2 million, total, since this comprises two easily-identified categories. The estimate of an additional $7 million for all the other “materials research,” includes the materials work in the science and engineering departments at universities which have a materials department but no materials center, and also the “non-center” part of the work in those cases where a center exists. In addition, to obtain the total federally funded materials research at universities, we include the work supported in the science and engineering departments at several dozens of the largest advanced degree-granting institutions in the country, which have neither a materials center nor a materials department. The resulting total is close to $75 million per year.

In the following section, the research being conducted at the universities within the scope of materials science and engineering is discussed under the

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* Interagency Council on Materials

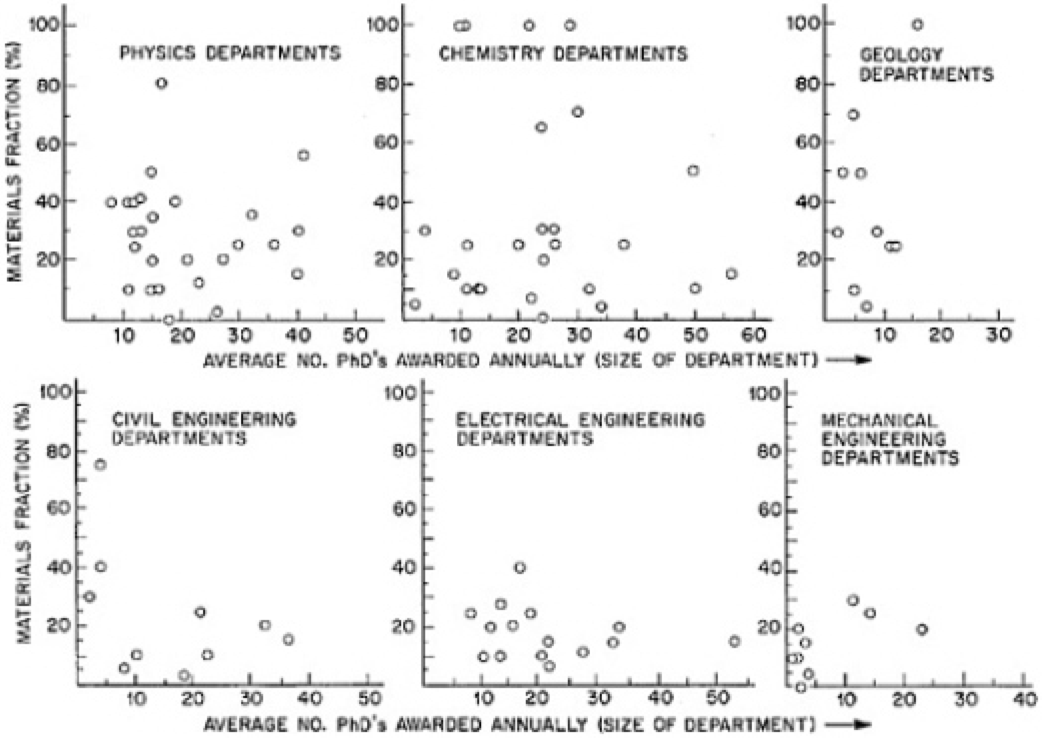

FIG. 7.36 DEGREE OF “RELEVANCE” TO MSE OF VARIOUS DISCIPLINES

TABLE 7.36 Distribution by Field of Science of Federal R&D Support to Universities for FY 1970*

Field	Amount (Dollars in Thousands)	Percent of Total
1. Physical Sciences:	283,114	20.28
Astronomy	32,111	2.3
Chemistry	70,205	5.03
Physics	176,629	12.65
Physical Science (n.e.c.)	4,169	0.30
2. Mathematics:	44,582	3.19
3. Environmental Sciences:	106,722	7.65
4. 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 (n.e.c.)	27,696	1.98
5. Life Sciences:	565,094	40.48
6. Psychology:	62,298	4.46
7. Social Sciences:	47,144	3.43
8. Other Sciences (n.e.c.)	144,748	10.37
	$1,395,923	100.

* Courtesy of Dr. C.Falk, NSF.

** A substantial fraction of the support within these categories is also devoted to materials research.

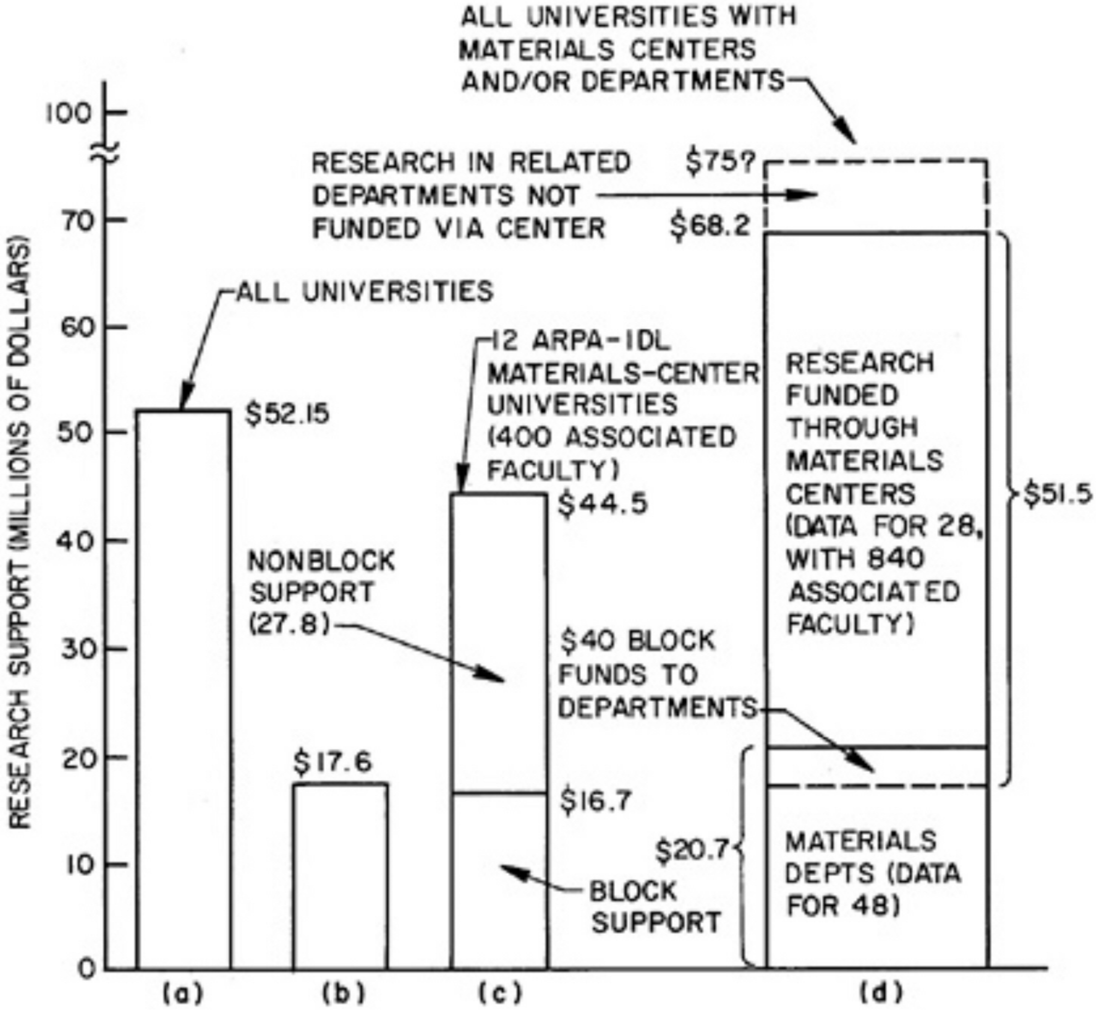

FIG. 7.37 DATA ON SUPPORT FOR MATERIALS RESEARCH AT U.S. UNIVERSITIES IN FY 1971

(a) INTERAGENCY COUNCIL ON MATERIALS SURVEY OF TOTAL DIRECT FEDERAL SUPPORT FOR MATERIALS RESEARCH IN UNIVERSITIES.

(b) NATIONAL SCIENCE FOUNDATION DATA FOR DIRECT FEDERAL SUPPORT FOR “METALLURGY AND MATERIALS” (DEPARTMENTS) RESEARCH IN UNIVERSITIES.

(c) NATIONAL SCIENCE FOUNDATION DATA FOR MATERIALS RESEARCH AT THE 12 NSF-MRL (ARPA-IDL) UNIVERSITIES.

(d) DATA FROM COSMAT UNIVERSITY QUESTIONNAIRE.

following headings:

- Research in materials research centers (interdisciplinary materials research laboratories)
- Research in the materials-designated departments
- Research coupled with industry

Materials Research Centers (Including Interdisciplinary Materials Research Laboratories)

It has been rightly claimed that formation of the materials research centers constituted a major landmark in experimentation with federal support of university research. Correspondingly, an evaluation of the experiment in terms of research administration, of the nature and quality of the research programs, and the interdisciplinary interaction developed, has significance beyond the materials field.

Currently, there are 28 universities in the U.S. with officially designated materials centers. While these centers go under a range of titles at the different universities, the term “materials center” will be used here to refer to any such officially constituted center or laboratory with materials as its focus and involving several disciplines. These centers include four limited in scope to one class of materials, e.g. polymers—but no less interdisciplinary. The centers have been supported predominantly by various federal agencies, some with block* grants, some without. A simple classification of the centers can be made on the basis of their source of support as given in Table 7.37. (Note that some universities appear in more than one place in the subsequent tabulations.)

The COSMAT questionnaires provided a description of the activities of these centers, together with the principal related activities in materials research. All these centers provided data, though that for one were incomplete. The findings presented here also include opinions regarding centers from a sample of senior materials research administrators in industry, government, and academia.

Table 7.38 summarizes the main characteristics of the university activities in materials research; Table 7.39 lists research capabilities of the materials centers; Table 7.40 indicates the distribution of support for the total materials research on campus; and Table 7.41 gives the support data for the materials-designated departments.

From analysis of the data in these tables, a useful classification of the centers on the basis of their principal distinguishing characteristics is the

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* A block grant is awarded to an institution, rather than to an individual; it implies that the decisions on exactly what research is done are made locally.

TABLE 7.37 Universities with Materials Centers in the U.S.*

GROUP I.	Block Supported by AEC—3 (U. Calif., Berkeley; U. Illinois; Iowa State)
GROUP II.	Block Supported by ARPA—12 (Brown U.; U. Chicago; Cornell; Harvard; U. Illinois; U. Maryland; M.I.T.; U. North Carolina; Northwestern; U. Pennsylvania; Purdue; Stanford)
GROUP III.	Block Supported by NASA—3 (R.P.I.; Rice; U. Washington)
GROUP IV.	Block Supported by JSEP—1 (U. Southern California)
GROUP V.	No. Block Support—10 (Case-Western; U. Connecticut; Lehigh; U. Missouri, Rolla; Penn State U.; U. Wisconsin; Washington U.; St. Louis; U. of Akron; U. Massachusetts; U. Utah) (The last three have institutes dealing with only one class of materials—polymers.)

* For statistical purposes, only organizations in existence for more than three years at the time of the survey are included. The materials center at the University of Illinois is sponsored by both AEC and ARPA.

TABLE 7.38 Materials Activities at Universities with Materials Centers, 1971

				Industry Coupling		Interdisciplinary Index	
Materials Center Building	Major Materials Departments	New degrees in Mat. Sci. or Solid State	“Strength” of Interdiscip. Administration	Official Program	% Res. Support	% Joint Contracts	% Joint Papers
			XX			–	5
X			X		2	8	13
X			X				26
X	X		XXX			2	1.3
			X			2	1.3
X	X	X*	XXX				
			XX			16	10
			X		0.2	20	5
X	X	X*	X			–	–
X	X		XX			1	5
						10	2
			X			2	2
X	X	X	XXX		1	44	19
X	X	X	XXX	X	7	40	10
X	X		XX	X	1.0	40	25
			X			5	5
X(?)			XXX		3	80	92
X		X	XX			–	–
		X	X			33	18
X	X		X	X	20	53	12
			XX			20	5
X		X	XXX	X(?)	0.1		

				Industry Coupling		Interdisciplinary Index	
Materials Center Building	Major Materials Departments	New degrees in Mat. Sci. or Solid State	"Strength" of Interdiscip. Administration	Official Program	% Res. Support	% Joint Contracts	% Joint Papers
	X		XX				
X		X	XX		15	10	10
X	X		X	X		25	–
			X			0	3

* X* = Mat. Sci/Eng degree subsumed previous metallurgy degree.

TABLE 7.39 Research Capabilities of Materials Research Centers at Universities, 1971

Total External Research Support via Center (1000$)	Facilities in Center		Faculty			Support via Staff		
Research Space 1000 sq.ft.	Equipment (1000$)	Total	Partly Paid	FTE Paid	Postdocs	Technicians	Secretaries	
7,279	210	10,000	84	74	41	139	63	23
3,648	67	2,250	52	44	13.9	34	21	8
3,456	85	4,259	45	39	8.9	29	14.5	16
3,588	53	2,670	36	36/3	10	28	35	12
2,943	85.2	1,400	39	32	5.52	0	13	.5
3,799	35	1,900	57	57	12**	61	30	11
3,420	60	2,500		53	10	115	86	70
1,832	41.8	1,050	48	30	3.1	9	3	3.5
*2,400				58				
1,562	46.5	1,690	38	38	14.2	8.5	8	6
2,197	100	3,000	44	44	8	29	4	8
1,794	40	550	24	13	3.5	46	9	9.5
1,560	35	600	35	29	8**	18	2	2
1,332	69	2,100	62	13	13	7	8	5
1,190	40	1,000	36	25	12	27	6	7
1,132	34.5	700	89	60	25	35	10	24
676	40	660	50	6	1	11	6	1
480	20	1,200	12	16	7	7	4	2
400	8.5	1,000	11	~11	~3		0	2
450	5	250	8	6	3.5	1	3	1.5
380	6.2	220	14	10	7.2	5	2	1.6

Total External Research Support via Center (1000$)	Facilities in Center		Faculty			Support via Staff		
Research Space 1000 sq.ft.	Equipment (1000$)	Total	Partly Paid	FTE Paid	Postdocs	Technicians	Secretaries	
250	15	400	19	2	0.5	3	0	3
240	45	2,000	45	8	3.4	6	5	1.5
310	11	300	17	14	~2	1	0.5	1.5
225	33	1,500	12	12	8	6	8	2
225	40	334	26	5	1	3	1	3.5
210	2	14	4	4		5	4	.5

* Data from this university are only fragmentary.

** Prorated from other data provided.

TABLE 7.40 Support for Materials Research at Universities, 1971

Funds to Center						Support to Academic Depts.	
Total (in $10^6\$$)	From Block Funding (in $10^6\$$)	Total Support Other Than Block and University (in $10^6\$$)	Support from Industry (in $10^3\$$)	Block Funds Per Member Receiving Support (in $10^3\$$)	Total Nonblock External Funds per Member (res. sup.) Received through Center (in $10^3\$$)	Research Support via Mat. Dept. Excluding Centers ($)	Related Departments with Substantial Research Activity[#]
8.02[*]	7.82[*]AEC	0		100.3	0	0.2	P,C,CH
4.83	2.8ARPA	1.15	92	63	89	0.25	C
4.28	3.69 ARPA AEC	0		94.6	0	0.2	P,G
3.9	3.6AEC	0	3	100.0	0	0.19	P,C.EE
3.9	0.85ARPA	2.09		26.6	65.3	–	
3.8	1.35ARPA	2.45		24	43	0.46	CH
(3.06)	1.35ARPA	1.92		25.5	36.2	No	P,G
(2.8)	1.08ARPA	0.95	8	36.0	31.7	0.23	P,C,G,CV
2.7	2.7ARPA	0		–	–	0.9	P,C.
2.6	1.97ARPA	0.06		51.8	2	0.45	C,CH
2.4	2.4ARPA	0		54.5	0	1.9	P,G,CH
(2.1)	0.8ARPA	1.0		61	69	–	
1.93	0.75ARPA	0.91		27.4	32	–	G
1.8	0	1.33	18	0	102.3	–	G,CH,CV
1.27	0[**]	1.11	90	0	45	0.56	P,C,G,CV
1.25	0.7JSEP	0.43	124	12	7	–	C
0.76	0.71ARPA	0.04		118	7	–	
0.71	0	0.48	20	0	30.0	0.12	

Funds to Center						Support to Academic Depts.	
Total (in 10^6\$)	From Block Funding (in 10^6\$)	Total Support Other Than Block and University (in 10^6\$)	Support from Industry (in 10^3\$)	Block Funds Per Member Receiving Support (in 10^3\$)	Total Nonblock External Funds per Member (res. sup.) Received through Center (in 10^3\$)	Research Support via Mat. Dept. Excluding Centers (\$)	Related Departments with Substantial Research Activity[#]
0.50	0	0.4	100	–			C
0.46	0	0.45		0	75	–	
0.42	0	0.38	103	0	38	0.83	CH
0.38	0.25NASA	0		–	–	0.13	P,EE
0.33	0	0.24	7	0	30	1.3[@]	P
0.32	0.25NASA	0.01	10	18	2	0.45	C
0.30	0	0.225	45	0	18.8	–	C
0.24	0.23NASA	0		46	0	0.73	P,G
0.2	0	0.21		0	53	0.66	P

* These figures are approximate estimates of a larger total effort supported at the university.

** A year-to-year contract with ARPA averaging near 0.28M, limited to one area, was a major factor in the funding here.

[@] This figure includes a “polymer institute” funded at 0.72 which should possibly be counted as a second materials center (i.e., in column 1).

(__) Numbers in parentheses mean that the unit actually handling the Materials Center work has a wider scope than just materials, e.g., a “Division of Applied Science.”

[#] “Activity” in related departments recorded where self-analysis indicates more than 25% in MSE. P=Physics; C=Chem; CH—Chem. Eng.; G=Geology; EE=Elec. Eng.; CV=Civil Eng. (See text.)

TABLE 7.41 Research Support in Materials-Designated Departments at Universities Having Materials Centers, 1971

Total (in 10^6\$)	From Block Funds (in 10^6 \$)	Total Less Block and University Support (in 10^6\$)	Support from Industry (in 10^3\$)	Research Support per Faculty Member (Including All Faculty: in 10^3 \$)		
From Center	All Other Sources	Total				
0.34	0.32	0.014	3	53	3	56
1.06	0.85	0.21		65	16	81
0.72	0.41	0.24	38	51	31	82
0.19				–	–	
–				–	–	
0.46		0.46	–			
1.5*	1.3	.2	48	11	22	33
0.41	0.18	0.17	65	36	34	70
1.22	0.28	0.94	12	26	85	111
0.45	–	0.39		–	26	26
2.41	0.53	1.9	298	20	72	92
–				–	–	
–				–	–	
–				–	–	
0.57 (1970)	0	0.44	153		13	13
–				–	–	
–				–	–	
0.12	0	0.07	42.5	0	6	6
0.5	0	0.5		–	–	
–				–	–	

Total (in 10^6\$)	From Block Funds (in 10^6\$)	Total Less Block and University	Support (in 10^6\$) Support from Industry (in 10^3\$)	Research Support per Faculty Member (Including All Faculty: in 10^3\$)		
From Center	All Other Sources	Total				
0.94	0.10	0.599	198	8	50	58
0.19	0.06	0.10	–	–	–	
1.36	0	1.32	333	0	65	65
0.78	0.32	0.46	16	160	230	390
–						
0.83	0.11	0.62	125	8	44	52
0.66	0	0.616	15	0	41	41

* This refers to a larger unit.

following (Note: Within each group, the schools are listed alphabetically):

GROUP A: Major Materials Institutions (MMI). Institutions which have a materials-center building providing a physical and intellectual focus for major materials research programs, relatively strong centralization of administration, a major degree program in materials, together with strong materials research in solid-state physics and chemistry.

University of California (Berkeley)
Case Western Reserve University
Cornell University
University of Illinois
Lehigh University
Massachusetts Institute of Technology
Northwestern University
University of Pennsylvania
Penn State University
Rensselaer Polytechnic Institute
Stanford University

GROUP B: Major Materials-Teaching and Research Schools (MTRS)*. Institutions which have a major and/or specialized research program in materials science or engineering and an official though small centralized research laboratory.

University of Connecticut
University of Massachusetts
University of Missouri
University of Southern California
University of Washington

GROUP C: Materials Research Programs (MRP). Institutions with materials research programs not focused in a centralized laboratory, but often large and typically strong in the basic sciences, and run by a committee of senior faculty, with no (or small) materials-designated degree programs. The term “materials research program” MRP, appears accurately to distinguish the typical characteristics of such centers from the laboratories of the MMI above.

University of Akron
Brown University
University of Chicago
Harvard University
Iowa State University
University of Maryland
University of North Carolina
Purdue University
Rice University
University of Utah
University of Wisconsin
Washington University (St. Louis)

At this point, it may be useful to review briefly the initial objectives of the materials-center concept as a precursor to examining their present character and effectiveness. (The origin of the concept and the history of the initial centers in the early 1960’s, following upon the recommendations to the Coordinating Committee on Materials Research and Development (CCMRD) of the Federal Council for Science and Technology (FCST), are outlined in Appendix 7C.) In the late 1950’s, federal agencies, particularly the

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* The newly established Processing Research Institute at Carnegie-Mellon University would likely place in this category.

defense agencies, were already investing heavily in materials research at universities. A widespread belief developed that many more Ph.D. graduates would be required to work on the development of the new materials technologies needed by the aerospace and atomic-power industries and by the defense and other national programs of the period. It was recognized that solution of associated advanced materials problems depended on integrated contributions from a number of scientific and engineering disciplines. The strong pace of solid-state science pointed to a need to broaden and strengthen correspondingly the scientific background of many of the Ph.D. graduates entering the materials field. The idea of interdisciplinary materials centers arose as a means of meeting these various needs. A novel feature of the original federal advisory committee recommendation was the block-grant funding mechanism, whereby the decision process for selecting individual research topics was transferred from the agency to the campus. Later in the 1960's, following the establishment of more than a dozen centers on this federal block-funding basis, a number of other universities organized centers without such support. Instead, they derived support from a variety of sources, including the university and the state, but principally by the aggregation of smaller contracts. Currently, about one-third of all the centers operate in this way.

The general objectives of the initial block-funded materials centers were defined by the work statements accompanying the contracts with the universities from ARPA and AEC. These statements were as follows:

(a) Work Statement for Interdisciplinary Laboratory Programs in Materials Science Supported by the Advanced Research Projects Agency, Department of Defense

"The contractor shall establish an interdisciplinary materials research program and shall furnish the necessary personnel and facilities for the conduct of research in the science of materials with the objective of furthering the understanding of the factors which influence the properties of materials and the fundamental relationships which exist between composition and structure and the properties and behavior of materials. To this end, theoretical and experimental studies in such fields as metallurgy, ceramic science, solid-state physics, chemistry, solid-state mechanics, surface phenomena, and polymer sciences shall be conducted, as well as other research investigations which may be mutually agreed upon by the contractor and the Advanced Research Projects Agency."

(b) Work Statements for Materials Laboratories Supported by the Atomic Energy Commission. Research to be Performed by Contractor (1962)

"1. The scope of the work under this agreement is unclassified and shall consist of research as may be mutually agreed upon by the contractor and the Commission in the broad fields of ceramics, chemistry, metallurgy, and solid-state physics. The research will be directed toward or supportive of the furtherance of a fundamental understanding of the nature of materials, predominantly solids. Because of the strong interest of the Commission in radiation effects and in the influence of defects, both chemical and physical in the properties of matter, it is anticipated that particular, although by no means exclusive, attention will be devoted to the study of defects in solids or surfaces.

2. The work will also include such other studies, investigations, and services in this general area as may be mutually agreed upon between the parties.

Research to be Performed by the Contractor (Modification in 1967)

The scope of work under this contract is unclassified and shall consist of research in the broad fields that follow:

1. Metallurgy and Materials Research
2. Physical Metallurgy and Ceramics
3. Materials Properties and Processes
4. Structure of Materials
5. Solid-State Physics and Crystal Physics
6. Energetic Particle Interactions

This research shall be directed toward, or in support of, furthering a fundamental understanding of the nature of materials, particularly solids."

While neither of these agency work-statements mentions education or the training of manpower as an objective (this area was outside the DoD and AEC authority), it is clear that starting such programs at universities implied such a goal also. Discussions during the COSMAT study with administrators involved in the initial materials center programs indicate that their general perception of the intent of the federal agencies in initiating these laboratories was as follows:

a) To develop the basic sciences of materials to new levels of sophistication and to develop an applied science which could harness this new knowledge to national efforts to solve advanced materials problems.
b) To increase the number of Ph.D. graduates trained in these developing pure and applied sciences.
c) To establish university research units which would emphasize interdisciplinary activities in research and teaching.

Consideration is now given to describing the principal resources for materials research at those universities with materials centers—funding, space and equipment, faculty, students—and to the corresponding research emphasis, output, extent of interdisciplinary effort, and interaction with industry that has developed.

Data on research support for the 28 institutions were listed in Tables 7.39 and 7.40. It is important to exercise some caution in interpreting this information. For example, the data reported in the column on Total External Research Support via Center will vary in meaning depending on local administrative arrangements. In some cases, the center appears to be principally a vehicle for the distribution and management of the single block grant (e.g., M.I.T., Northwestern, Illinois). At the other end of the spectrum, there are centers which serve principally as the main channel for materials research support for faculty from several departments (e.g., Chicago, Iowa State) or in a larger administrative unit which incorporates the center (e.g., Brown, Harvard). Unfortunately, it has proved difficult to determine accurately the total materials research support at any university because the term "materials research" is interpreted differently at different institutions and the nature of record-keeping also varies widely.

The best index of materials research activity at a given university appears to be given by a composite of three columns in Table 7.40. The first lists block-funded support via a materials center, which is known unambiguously. The second lists the research support via the materials departments which is also accessible, although there may be some modest overlap with the center in allocating technician and facility charges, etc. The third column names the related departments which have indicated that their faculty are involved in materials research to an extent "greater than 25%"; it was not feasible to assign research-support levels here. In some instances, the figures for research support in the materials center include only the funds administered or processed explicitly by the center. This may be the single block grant only, but in other cases it may include 50–100 individual contracts for research within the interdisciplinary setting of the center. In still other cases, where the figures are for the total research of all the faculty members affiliated with the center, these numbers tell little about the materials research on a campus, inasmuch as many of the faculty in the related departments may devote only a portion of their total research to the materials field.

Despite these shortcomings in detailed information, the tables indicate significant general characteristics concerning the overall scale of activity. Thus, there are some dozen institutions with total annual materials-research funding above $2 million (including six at $4 million or greater), and a half-dozen institutions at the other end of the scale with annual funding below $0.5 million. The variation in the size of the block grants ranges from $4.25 to less than $0.3 million annually. In fact, the centers tend to fall into three groups, with 9 having block support in excess of $1 million/ year, 9 having block support of less than 1 million, and 10 having no block support at all. The larger 9 receive 85% of the total available block support ($22.5 million) and the middle 9 some 15% ($4.6 million). An unexpected finding is the circumstance that, among these three groups, the nonblock-supported group has some well-established programs with buildings, degree programs, etc., even larger than the block-supported groups. Also, the middle group includes a number of major materials institutions despite the lower support level.

The division of support of the total materials research at the universities with materials centers has changed substantially over the 1960's and early 1970's, especially over the past five years. After FY-1974, the National Science Foundation dominates the support picture, with about 50% of the total. The initially dominant DoD proportion diminished significantly in that period, even aside from the ARPA transfer of the IDL program to NSF. However, while there had been some expectation that civilian agencies such as the Department of Transportation and the Department of Housing and Urban Development would begin to increase their support for materials research, this has not yet developed in a substantial way.

For space and equipment, the COSMAT returns indicate that the major centers involve between 30,000 and 80,000 net sq. ft. of laboratory space. Capital equipment among the centers shows a much bigger spread, even in equally well-funded laboratories. The minimum for a substantial operation would seem to be about $500,000, while a major center appears to require equipment in the range of $2 million. There is a good correlation between the scale of block funding and the amount of equipment at the centers.

The number of faculty associated with each materials center (Table 7.39) varies from 4 to 89, with 50% of the centers each involving between 20 and 50 faculty. The full-time equivalent (FTE) faculty members paid through center funding varies correspondingly; for universities receiving between $1 and $4 million annually, the number of such faculty ranges from 3.5 to 25. In any assessment of the effectiveness of a center, the total materials research of all faculty who are members, whether paid by the center or not, is an important indicator of the total university effort. The level of active participation in, and intimate concern for, the affairs of a given center by the faculty involved is likewise an important factor. Attempts to measure these parameters are difficult, and the delineation of the FTE faculty paid through the center is one such attempt. (In most universities, it has been common practice to charge outside contracts approximately in proportion to the faculty member's time devoted to that particular research and hence the FTE faculty paid could be the best measure of research involvement.) In view of this significance, a revised second questionnaire was mailed to respondents to try to insure that there had been no misunderstanding as to the definition of full-time equivalent. No changes resulted.

From the data returned, of those faculty receiving some salary support from center funds, the average FTE involvement is found to be between one-third and one-fifth of the salary. However, it appears likely that some universities may have paid some research salaries under research categories other than the materials center, although the activities might be relevant to the center. Others may not have charged any grants for research time. Finally, it was not always clear from the data that the FTE returns were referring to the same year (academic or calendar) in all cases. In trying to estimate the possible effects of such uncertainties on the data, it was recognized that some faculty members may concentrate their research in the summer months and, in addition, may devote up to half their time to research during the academic year. Hence, a few faculty members, very active in research, could be devoting two-thirds of their time to research on a 12-month basis. In cases where the universities do not charge the contracts for the research time of the faculty, they would have underestimated the FTE involved. Comparing the averages noted above and the maximum research activity estimated to be possible, it would appear that for an institution where all of the “exceptional” circumstances are realized, which is the unlikely extreme case, the effect could be a factor of two. Given this assessment of the FTE faculty parameter as an indicator of faculty effort in the centers, its relation to total center funding can be examined for the full spectrum of centers currently in operation. Such a relation is plotted in Figure 7.38 to provide a measure of the total center support for one hypothetical faculty member’s research program, who devoted full time to research with a complement of postdoctorals, graduate students, technicians, and his share of central-facility costs. Figure 7.38 shows that there are several universities where the ratio of annual center support to FTE faculty exceeds $500,000/FTE and that there are only a few where it is less than $100,000/FTE. The ratios should not necessarily be interpreted as the cost of a FTE-supported man-year of faculty research, but the rather large differences in the investments per unit of faculty time do point up the need to examine the corresponding variations in what results from such investment. This concern will be addressed later.

The above figures for research at the materials center provide some useful budgetary indicators for administrators. Thus, a major materials center at a university would seem to require a minimum effort of 10 to 15 FTE faculty members. An annual average dollar support per FTE in the range of $200,000 to $250,000 should be anticipated. The total associated research support of a faculty group of, say, 30 active participants, each involved one-third time in research and associated students, postdoctorals, and technicians, would be at least $2 million per year. If the group consisted of as many as 50 faculty, a total minimum annual budget of about $4 million appears necessary. Such a group would seem to need a total capital equipment inventory of about $2 million.

As to research emphases at the various materials centers, the data obtained through the COSMAT questionnaire were not sufficiently informative. General impressions of the research in the 12 laboratories started under the ARPA-DoD program are given by the disciplinary distribution of the faculty involved:

Number of Associated Faculty	1967	1971
Physics	200	143
Materials	110	98
Chemistry	100	102
Electrical Engineering	30	41
Other Engineering, Math., Science	30	24
	470	408

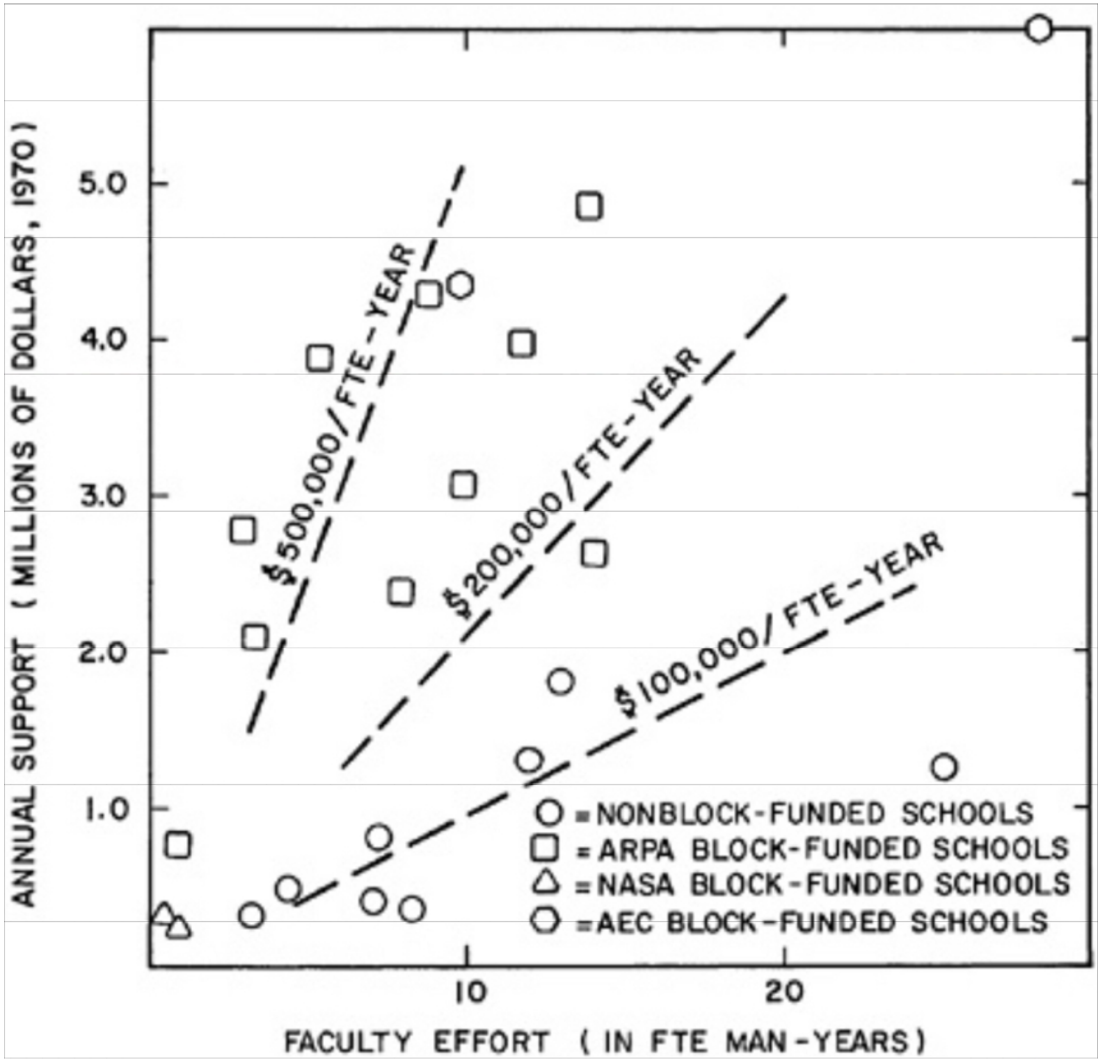

FIG. 7.38 ANNUAL SUPPORT VERSUS FACULTY EFFORT ASSOCIATED WITH UNIVERSITY RESEARCH IN MATERIALS

Furthermore for both the AEC and ARPA laboratories, while work statements of the block grants of over a decade ago mentioned all classes of materials, specifically including ceramics and polymers, the qualitative evidence is that these classes of materials received much less attention than did metals and semiconductors. However, in many centers this imbalance has begun to be rectified in recent years. Nevertheless, all the major materials programs concerned principally with polymers have grown up in nonblock-funded laboratories. An analysis of the 28 laboratories's plans for future emphases, as compared to their present, indicate that, without exception, there is a desire to extend their programs in the applied direction. However, the new research areas most frequently proposed are in biomaterials and substantially more effort is being projected there than for ceramics or polymers. These two directions of future change appear somewhat inconsistent in that the magnitude of the industrial technology associated with ceramics and polymers is enormous compared to that for biomaterials.

We turn now to the question of the product of the research carried out by the materials center, i.e. knowledge about materials. Most commonly this knowledge is communicated to the scientific and engineering world by publication in specialist journals and other publications. A valid measure of the effectiveness of the contributions from a particular center is hard to obtain because the overall impact is obviously dependent upon factors such as quality, as well as on number of publications. Some research which has had a major influence on the direction of science has been published by faculty members whose rate of publication may be low. However, a useful index can be obtained if the count of the number of papers is restricted to those published in refereed journals, and if the reported data refer to a large group of scientists, to individuals over a large period of time, and to a coherent subject-matter field. In the COSMAT inquiry, all these conditions were reasonably well satisfied. The resulting data are shown in Table 7.42 in terms of papers per year per faculty member. It is evident from these figures that while some trends may exist, the total faculty and total output of a center as tabulated here may not provide a proper assessment of the materials research on a given campus. In other words, the spread in data is worthy of note and it also appears that some universities with outstanding reputations may rank rather low on those scales.

It is instructive to compare the ratios of materials-center support to the number of published papers for the various universities. From the responses to the COSMAT questionnaire, averages over a large group and over five years could be computed. The results are shown in Figure 7.39. Here again, there is a wide range of values, from below $10,000 per paper to above $40,000 per paper. While there are other products or outputs resulting from the same support, these relative figures are of interest, since publications are usually considered to be the major indicator of the amount of new knowledge generated. The ratio of dollar support to another principal product of university research—the number of graduate degrees per year— was also computed and is plotted in Figure 7.40. Unfortunately, the

TABLE 7.42 Research Output of Materials Centers (Ranked in order of Papers/Paid+ Faculty)

Number of Papers Per Year*	Papers/Total Faculty	Papers/Paid Faculty	Papers/FTE
206	3.62	10.3	17.16
28**	1.47	7	28
90	1.45	6.92	6.92
32	1.24	6.4	32
148	4.22	5.28	18.5
124**	3.44	4.96	10.33
143	2.97	4.76	46.12
57	2.37	4.38	8.76
137	3.51	4.28	24.9
153	4.22	4.22	15.3
24**	0.48	4	24
144**	3.2	3.69	16.17
199**	2.36	2.68	4.85
96**	2.52	2.52	6.76
25***	1.8	2.5	3.47
103	1.99	2.34	7.41
110**	–	2.07	11
24**	2	2	3
26	2.16	1.62	3.71
33	0.76	0.76	4.1
3	0.75	0.75	–
35	0.39	0.58	1.4
8**	0.47	0.57	0.57

* 4-yr average unless noted.
** 5-yr average
*** 3-yr average
\+ Paid Faculty means paid by the center.

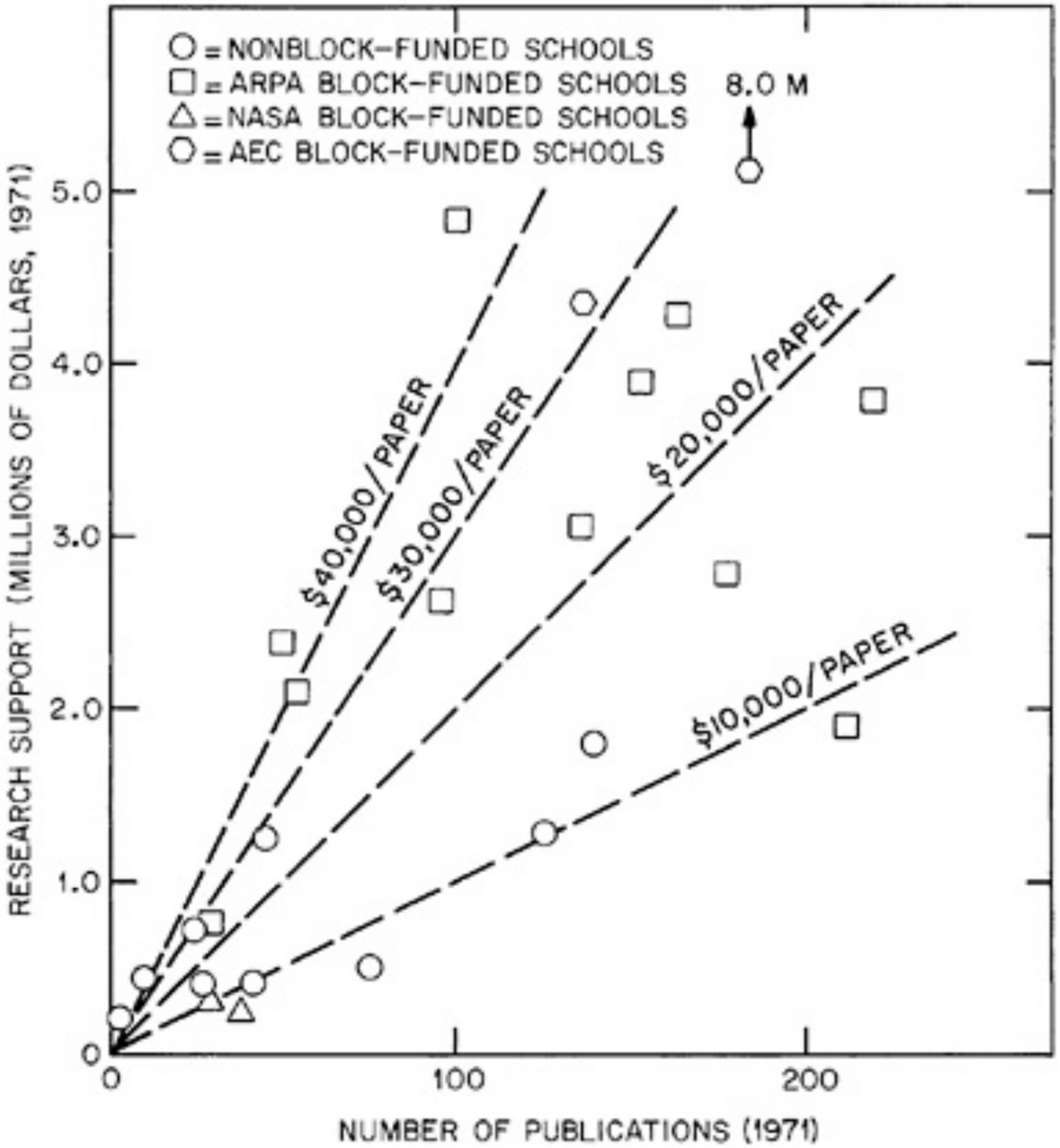

FIG. 7.39 ANNUAL SUPPORT VERSUS NUMBER OF PUBLICATIONS AT MATERIALS CENTERS

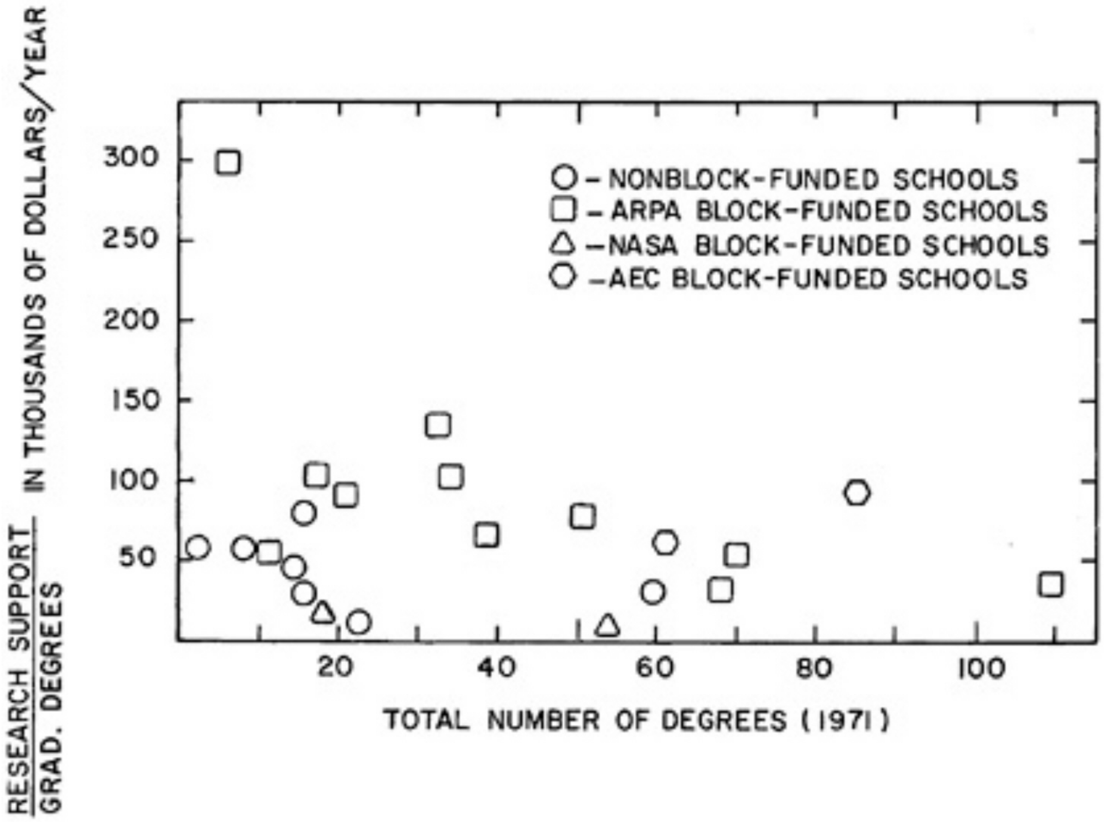

FIG. 7.40 ANNUAL MATERIALS RESEARCH SUPPORT/GRADUATE DEGREES VERSUS NUMBER OF GRADUATE DEGREES

questionnaire combined M.S. and Ph.D. degrees, and so the data are not as fully informative as they might have been. Again, analogous to the publications, it must be emphasized that any attempt to identify this ratio uniquely with costs involved in training graduates would be misleading. What these various results do show is that there are large variations from school to school in the research support per year required to result in a paper or a graduate. Hence, depending on whether the principal result sought is research papers or graduates different choices might be made to obtain the most appropriate result for which the research support is intended.

In view of the initial IDL center objective of fostering interdisciplinary research, an attempt to measure the degree to which the centers have been able to develop such interdisciplinarity was undertaken by asking the centers to report on the "number of joint programs," meaning programs on which the principal investigators were from different departments, and the number of joint papers per year. The returns relating to joint publications proved to be more complete, although a few of the major centers failed to report. These results show that in at least three-quarters of the centers, 5–10% of the papers published per year are written jointly by faculty from two or more departments (see Table 7.38, page 7–175). To some extent, these data underestimate the real interdisciplinary activity in that a number of the materials departments (Table 7.31, page 7–133) have recruited their faculty from a variety of backgrounds, and so papers written jointly by members of the same department could be interdisciplinary, and yet not appear in Table 7.31. The indications are that the number of "joint papers" across departments or disciplines published in other areas of science and engineering is much smaller than shown here. Thus, the publication records for materials research through the centers do provide evidence that an encouraging degree of interdisciplinarity has been achieved within the materials centers. Nevertheless, the fraction of "joint papers" is still substantially less than derive from the major interdisciplinary laboratories in industry, as discussed below.

Subjective views on the extent to which centers had succeeded in promoting interdisciplinary work were also requested by COSMAT. Many observers close to the materials centers, some of them being current or past center directors, expressed the view that the interdisciplinary activity was much more extensive and profound than is suggested by an examination of joint publications or contracts. For example, that by day-to-day contact with other members of the center, many faculty members had themselves become much more interdisciplinary in their own experience and outlook. It is also claimed that many interdisciplinary contributions may be important but still not reach the co-authorship stage.

In contrast to opinions from within the universities, the responses of senior materials administrators from outside the universities revealed much more mixed feelings about the achievements of the interdisciplinary centers; indeed, a few respondents expressed the view that interdisciplinary work had been achieved to only a negligible degree. Moreover, a study of the authorship of papers emanating from the materials research laboratory of a high-technology industrial research organization* reveals that their interdisciplinary publications were as high as 40%.

Since the most novel and distinctive feature of both the administration and funding in the materials area during the past decade was the interdisciplinary center, a survey was made by COSMAT of the expectations of the materials community, and the degree to which these expectations were met. Table 7.43 summarizes the results. It is interesting to note that "effective coupling to industry" showed up most poorly in the evaluations. Also, "Genuinely closely-coupled interdisciplinary research" was judged well below expectations. On the other hand, the centers "overperformed" in the traditional academic areas of educating students and individual research.

Interactions with industry by the materials research centers have been relatively modest. Only 5 (University of Pennsylvania, Southern California, Lehigh, University of Massachusetts, and Penn State) of the centers reported receiving substantial (approximately $100,000 per year) financial support from industry (Tables 7.40 and 7.41), and it constituted more than 10% of the budget in only 3 of these. However, the total research funds provided by industry for materials research at universities is substantially larger than it provides for the centers. Thus, Table 7.41 indicates that there are 5 departments with an average of over $200,000 each in industrial support, constituting over 20% (on the average) of the department's total research support. On the whole, though, the data reported in Table 7.40 reflect a sparcity of working interactions between most centers and industry. The attempts to establish productive interactions between university materials laboratories (departmental or center controlled) and various industries will be discussed later.

The data on the centers, as presented and discussed in the preceding pages, and including both the costs and the output in terms of students educated and research published form part of the essential information for

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* The staff of this laboratory comprises chemists, metallurgists (including ceramists), and physicists in about equal numbers. Their work ranges from basic research to engineering. They operate either singly or in col-laboration as appropriate. Their collaboration is with colleagues in the same laboratory and with others in other laboratories oriented primarily to studies of physical phenomena or the development of electronic equipment. The following tentative conclusions can be drawn in this connection:

(a) 129 out of 230 (i.e.56%) of the papers have 2 or more authors.
(b) 92 out of 230 (i.e.40%) of the papers involve authors from 2 or more disciplines.
(c) In mono-disciplinary papers, only 5 out of 44 (i.e. 11%) by chemists are by 2 authors or more, 12 out of 42 (i.e.29%) by metallurgists, and 17 out of 50 (i.e.34%) by physicists.
(d) Physicists figure more prominently in the multidisciplinary papers whether in collaboration with chemists, metallurgists, or engineers.
(e) Of the papers involving collaboration between 2 or more disci-plines, the great majority, 80 out of 92 (i.e.87%) involve just 2 disci-plines.

TABLE 7.43 Expectation and Performance of Materials Centers

(COSMAT Survey of Opinions)		Expectation	Performance
1. The most important goals which should be achieved by materials centers are: (on a scale of 5 (most important) to 1)	Genuinely closely-coupled interdisciplinary research	4.0	2.5
Training M.S. -Ph.D. personnel in Materials Science	3.3	3.7	
Support of individual faculty projects of excellence	3.3	3.7	
Establishing unique central facilities available to all	3.1	3.4	
Efficient start-up of new work	3.0	3.2	
Mission-oriented multiple investigator research	2.7	2.3	
Effective coupling to industry	2.7	1.5	
Applied research, possibly relevant to industry	2.2	1.7	
2. The general concept of long-range block funding for support of university materials centers is:	3 Very sound approach		2.35
2 Good but not essential			
1 Undesirable			
3. What is the “critical-mass” for a good materials research laboratory concentrating in even a limited area?	In man-years of senior faculty effort (i.e., each m.y. includes necessary postdocs., students, etc.)		10 man-years

		Expectation	Performance
4. If in your view it is a good approach, what median annual level of funding provides the best compromise in the typical major university between the benefit of stability and creativity and the possible loss of outside evaluation and responsiveness to national changes?	$ 250,000 500,000		
1,000,000 other	Av. $600,000		
5. The materials centers have devoted:	3 Too many resources to materials science & engineering departments or programs		
2 Good balance		1.5	
1 Too many resources to related fields; physics, chemistry, mech. engineering, etc.			

evaluating the effectiveness or "quality" of a center. One other approach to this difficult question may be found in attempting to assess the component departments whose faculties are involved in a center. This approach assumes that the quality of the associated departments can be taken as an index of the center quality. The appropriate information is available from the quality ratings of departments by the American Council on Education (ACE) as reported by Roose-Andersen in 1970, based upon questionnaires circulated in the spring of 1969. Taking the aggregate of the ACE ratings of the Departments of Chemistry, Geology, Mathematics, Physics, Chemical Engineering, Civil Engineering, Electrical Engineering, and Mechanical Engineering, results in a list which contains most of the universities with block-supported materials centers together with a few nonblock-supported centers. It has also to be emphasized, however, that many universities which have high-quality materials efforts, but without materials centers, such as Caltech, Princeton, U. Mich., also appear high in the AEC ratings.

Research in Materials-Designated Departments

It was noted earlier that the formally-designated materials departments carry out roughly one-third of the total materials research at the universities. In characterizing the research of these departments, of most interest is the emphasis on specific research topics, the resources applied, and the resulting output, i.e. what research is done, how much does it cost, and how effective is the research activity. The nature of the research emphasis proved to be difficult to ascertain. Surprisingly, none of the federal-agency analyses provides such information on the university sector. The only indication of the research scope obtainable was through the items of research interest cited by faculty of materials departments in the U.S. universities.[18] The results of this analysis, shown in Table 7.44, point to the relatively modest faculty interest in various aspects of processing; the stronger concentration on mechanical properties than on physical properties; the dominance of research on structure; and the limited effort on materials other than metals.

Specific data on the distribution of sources of federal research support for the materials-designated departments were presented earlier. The distribution of funds, by source, for such departments in 1971 is summarized in Table 7.45. The support total is close to $21 million. Of this support, some 20.5% originated in block funding. It is evident that DoD is the largest funding agency for the materials-designated departments, with 35% of the total. This is in marked contrast to the funding at centers where NSF has become the dominant agency.

The relation between the research support going to the individual materials-designated departments and the number of FTE faculty is shown in Figure 7.41, and the corresponding research support per faculty member is plotted in Figure 7.42. The latter indicates some tendency for the support per faculty member to rise with increasing departmental support and faculty size,

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[18] Directory of Metallurgy/Materials Education, J.Nielsen, editor, New York University (1970).

TABLE 7.44 Distribution of Areas of Faculty Research Activities in Materials-Designated Departments

		% of Cited Activities
MINING AND MINERAL BENEFICIATION		2.3
PRIMARY PROCESSING (Metals)		8.7
SECONDARY PROCESSING (Metals)		7.7
NATURE, DEVELOPMENT, AND CHARACTERIZATION OF STRUCTURE		
Fields	4.8	
Gases and Liquids	2.4	
Solids	1.4	
Phase Equilibria, Transformations, and Reactions	9.4	
Diffusion	3.3	
Lattice Defects	3.4	
Characterization	10.4	35.3
PHYSICS AND CHEMISTRY OF CONDENSED MATTER		3.2
PHYSICAL PROPERTIES AND BEHAVIOR		
Optical	0.5	
Electronic	2.5	
Magnetic	1.6	
Surfaces and Thin Films	2.8	7.5
MECHANICAL PROPERTIES AND BEHAVIOR		11.1
ENVIRONMENTAL EFFECTS ON PROPERTIES AND BEHAVIOR		
Corrosion and Oxidation	1.3	
High Temperature	1.3	
High Pressure	6.2	
High Energy Radiation	1.6	8.0
SPECIFIC MATERIALS*		
Metals	1.5	
Ceramics and Inorganic Glasses	5.9	
Polymers	2.9	
Composites	1.1	
Biomaterials	1.6	13.0
EDUCATION, HISTORY, AND ARCHEOLOGY		0.6
		100.00

* It appears likely from the nature of the Metallurgy/Materials Directory used for this tabulation that most of the research items not associated specifically with a given material relate to work on metallic materials.

TABLE 7.45 Source of Research Support for Materials-Designated Departments, 1971

SOURCE	PERCENT
Universities	9.0
Foundations	1.7
State Government	0.8
Industry	10.2
NSF	11.9
DoD	34.9
AEC	22.3
NASA	8.5
Other	0.6
	100.0

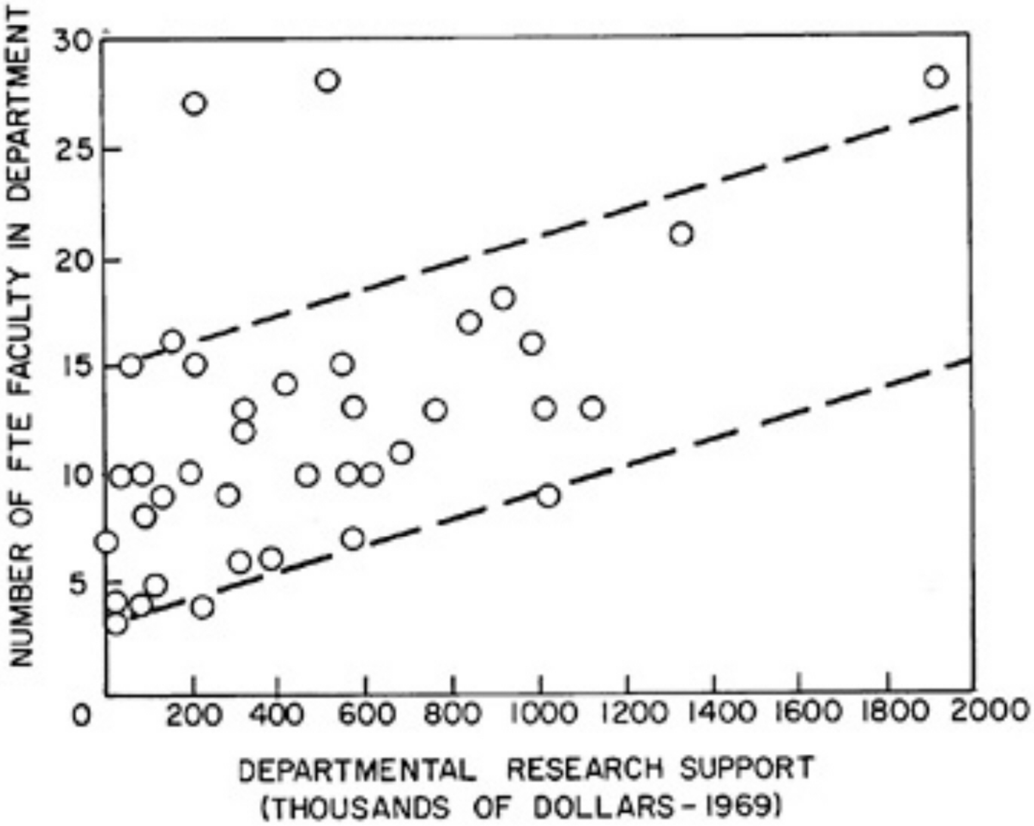

FIG. 7.41 RELATIONSHIP BETWEEN NUMBER OF FTE FACULTY IN MATERIALS-DESIGNATED DEPARTMENTS AND DEPARTMENTAL RESEARCH SUPPORT

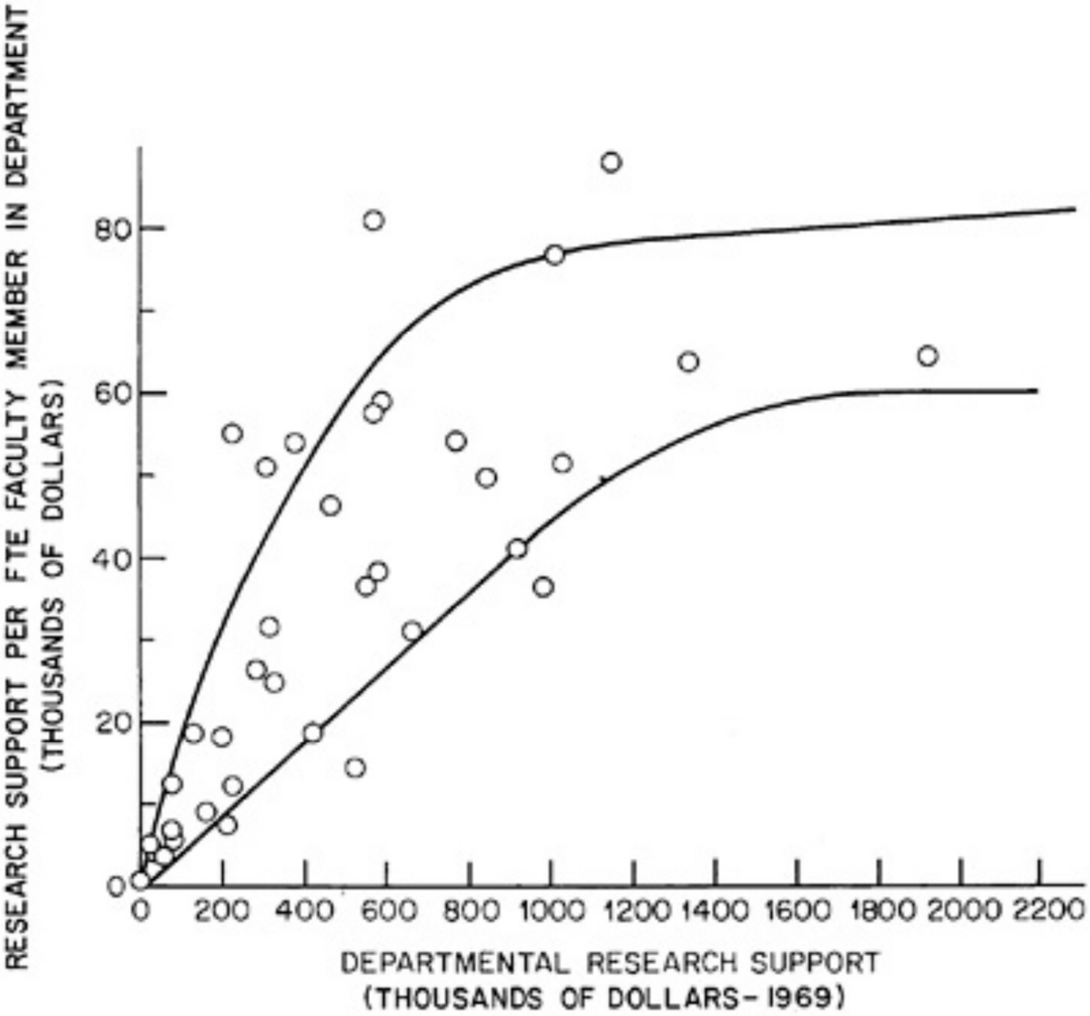

FIG. 7.42 RELATIONSHIP BETWEEN RESEARCH SUPPORT PER FTE FACULTY MEMBER IN MATERIALS-DESIGNATED DEPARTMENTS AND DEPARTMENTAL RESEARCH SUPPORT

but to level out at some $10,000 annually per faculty member when the departmental support exceeds about $1 million annually.

The doctoral and publication outputs corresponding to the above research support are presented in Figures 7.43 and 7.44. The relationship between the average number of doctorates awarded annually by a department and the level of annual research support (Figure 7.43) again shows a wide variation—from less than $50,000 to more than $150,000 per year per doctorate. Likewise, the research output expressed as the number of publications per faculty member in relation to the number of graduate degrees awarded (Figure 7.44) also shows considerable spread, with the faculty output generally increasing (up to 4.5 to 5 papers per year) as a function of increasing number of graduate degrees awarded by the department.

Research Interactions with Industry

The evidence from the COSMAT survey indicates that there is relatively little interactive research in materials being done jointly by the universities and industry. Specific coupling efforts exist in only 4 of 5 materials groups in the country. The most active of these are in four universities with materials centers having no block-fund support, and in one center having such support. Although the industrial perception tended to be that the degree of this interaction was too small, the universities alone do not appear to be accountable for this state of affairs; industrial management seems to have been unimaginative in its approaches to utilizing the potential resources of the federally-funded basic research groups at the universities. A longer discussion of the problems and opportunities of industry-university coupling, including descriptions of the various programs, is given in Appendix 7D.

Two basic patterns of coupling have been tried in the materials field: A: Industrial Coupling or Liaison Program between universities and industries alone; and B: the ARPA-coupled contracts and NSF experiments where the sponsoring agency serves a special role.

Pattern A

Lehigh University—“Industrial Liaison Program” —Materials Science Center with approximately a dozen companies. About 10 years old.

Penn State University—“Industrial Coupling Program” —Materials Research Laboratory with approximately a dozen companies. About 10 years old.

Stanford University—“Industrial Affiliates Program” —Chemistry and Chem. Eng. Departments with 13 companies. About 3 years old.

U.C.L.A. —“Materials Affiliates Program” —Materials Division with six companies. 3 years old.

Case Western Reserve University—“Industrial Coupling” —Macromolecular Institute and about a dozen companies. About 7 years old.

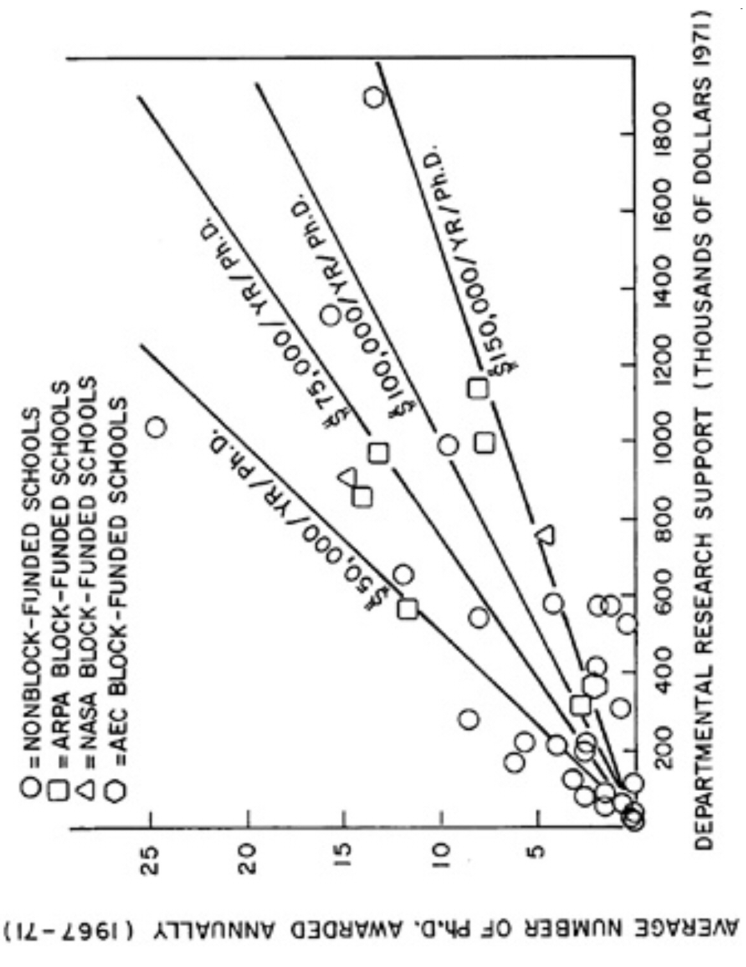

FIG. 7.43 ANNUAL NUMBER OF DOCTORATES FROM MATERIALS-DESIGNATED DEPARTMENTS IN RELATION TO DEPARTMENTAL RESEARCH SUPPORT

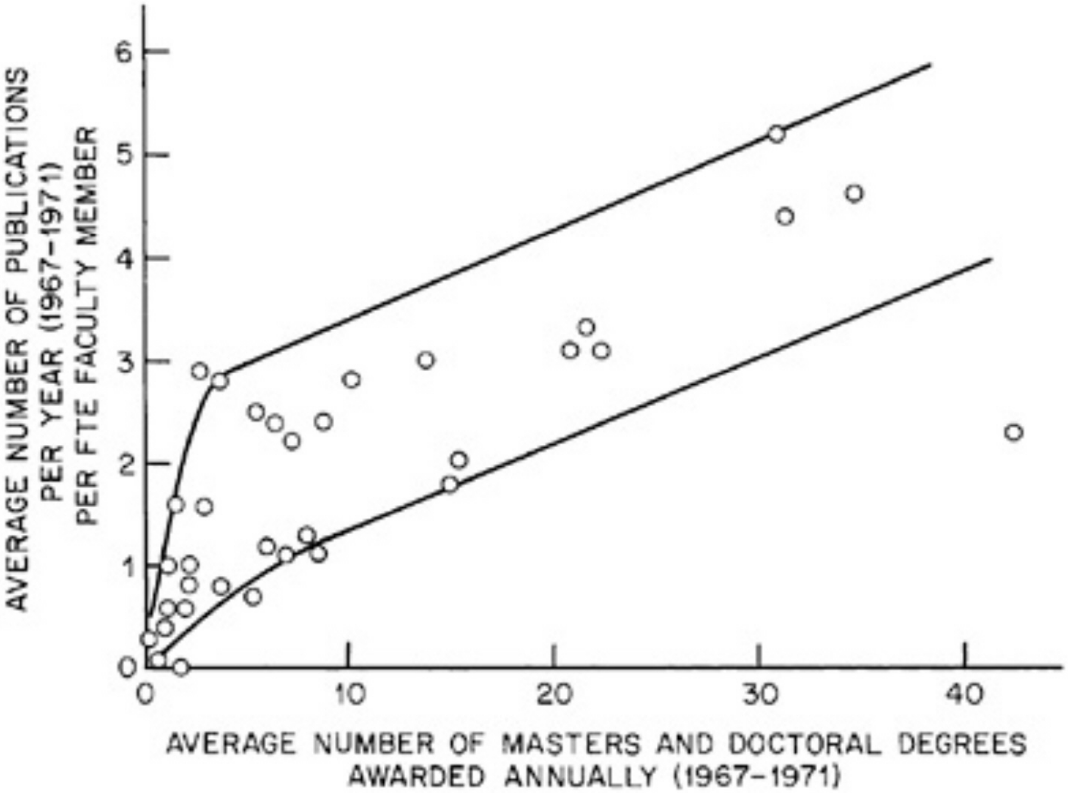

FIG. 7.44 RELATIONSHIP BETWEEN PUBLICATION RATE AND GRADUATE-DEGREE OUTPUT OF MATERIALS-DESIGNATED DEPARTMENTS

Pattern B

Washington University (St. Louis) — Monsanto (continuing)	All with ARPA support (about 8 years old)
Case Western Reserve University—Union Carbide (terminated)	
University of Denver—Martin Marietta (terminated July 1, 1973)	
American University, Carnegie-Mellon, Georgia Tech., Lehigh University Boeing—Naval Research Laboratory (terminated)	
Carnegie-Mellon University—“Processing Research Institute” —Mechanical, Chemical, and Materials Engineering Departments. (Just starting)	With NSF support
Seven Universities—Ultrahard Materials Program with 30–40 companies in cutting tool and grinding materials area.	

The ARPA approach was aimed very specifically at advancing selected areas of technology, on the basis of the following criteria:

(a) It must be of major DoD interest.
(b) It must be lacking in sufficient commercial interest unless stimulated by adequate DoD support.
(c) The field must be small enough that support of the order of a million dollars per year is enough to permit a laboratory operation to attain close to world leadership.
(d) The area must be large enough that it is not intellectually confining, so that good people will find a wide enough assortment of problems to attract and maintain their interest.
(e) It should be a field in which there is on-going work at present, “since we do not wish to attempt to build from scratch a large program that we then have to feel responsibility for.”

The ARPA experiment was basically not an attempt to innovate in interinstitutional interaction, but rather a program to accelerate science-technology transfer.

The principal active model, which emerges for the other and longer-lived programs, is of a small (10–15) list of companies, specifically associated in a formal manner with a particular laboratory. A key common feature is that the area of specialization of the university laboratory be of specific and particular interest to the companies involved. This is the crucial distinction from the generalized university-wide "industrial associates" programs which many distinguished universities have developed since the War. Thus, among the examples given, it will be seen that the Lehigh program attracts chiefly metals companies, while that at Penn State University chiefly attracts electronic materials and ceramics companies.

For the most part, interaction with industry was not a primary purpose of the federally block-funded materials research centers. Nevertheless, some of the block-funded centers have had wide-ranging, but informal, interactions with materials and local industries, and have participated in materials problems of practical interest. These interactions have occurred via informal discussions, by members of the centers acting as consultants to industry, by the participation of members in national problem-solving study groups such as the ARPA Materials Research Council, and by industrial research administrators serving on the visiting committees of materials centers.

Some General Aspects of Materials Science and Engineering at Universities

A variety of organizational units within the universities make a contribution to the science and engineering of materials. In the educational area, about 90 formally-designated materials degree programs of all kinds (including materials science, solid-state science, materials engineering, metallurgy, ceramics, and polymer science—alone or in various combinations) produce some 1000 B.S., 450 M.S., and 300 Ph.D. degrees per year. These constitute roughly 3%, 4%, and 8% of the corresponding numbers for all of engineering. In addition, several hundreds of bachelor's and advanced degrees are granted to students who enter the wider field of materials science and engineering; in that group of disciplines, physics, chemistry, electrical engineering, etc., some 500 Ph.D. degrees are awarded annually in university materials-related programs.

Educationally, MSE has a relatively weak presence on the campus as a disciplinary activity—having some impact on the engineering curricula and essentially none on science departments. Of the 250 or so engineering schools, only about 65 have departments of materials. In part, this state reflects the stage of development of the field. At many universities, materials as a field is new enough to be considered in an "interdisciplinary" phase.

Materials research is conducted within interdisciplinary centers, materials departments, and a wide variety of related departments. A particularly important development during the last decade in university research administration has been the emergence of the materials center and its block-funding concept. Nevertheless, a great deal of misinformation and misunderstanding appears to exist as to the current character and state of that area, even among those closely connected with the field. From the COSMAT analysis, the principal facts may be summarized as follows:

(a) There are some 28 interdisciplinary materials research centers of various kinds existing as formal units at institutions in the U.S. They receive about $51 million annually (FY '71) from all external sources to support their research.

(b) Eighteen of these are block funded, with the amounts varying from $250,000 to $7 million annually.
(c) Ten are not block funded, but a few of these are as large and diverse as several of the block-funded institutions.
(d) Taken as a group these centers constitute a major national resource for sophisticated education and research in MSE. There is general agreement in the universities that block funding on campuses is a desirable and workable arrangement. However, there is a wide spread in all the quantifiable measures of the actual performance of such centers. Within the materials community, considerable diversity of opinion exists on the effectiveness of block funding as a whole with respect to the costs for producing research and training students, the degree of interdisciplinarity achieved, innovation in education, and interactions with government or industry.

Research in the materials-designated departments is funded at about $20 million annually, followed in funding by materials research in departments of physics, chemistry, and electrical engineering.

Coupling of the university materials programs to industrial research has been modest. Generally speaking, the coupling experiments by ARPA do not seem to have left a major mark. Five formally organized programs coupling a materials center or unit to a group of industries exist, all save one at nonblock-funded universities. The adopted patterns have similar features, and provide a valuable starting point for other attempts.

The last ten years have been an era in which the conceptual and industrial aspects of the science of materials have been developed and refined, along with a burst of activity in the basic sciences. The next decade should see the test of the validity and utility of these concepts with thrusts toward the more applied areas.

A study of the objectives of the materials centers and of the important novel characteristics of the materials science/engineering field suggest certain criteria which may serve usefully in future evaluations of the materials-center programs, particularly in relation to national concerns. These criteria are:

(a) Effectiveness of materials center management.
(b) Outputs per dollar of support, development of unique central facilities to aid materials research across the whole campus, graduate degrees, publications.
(c) Quantity and quality of research and graduate students in both materials-designated and materials-related areas.
(d) Degree of interdisciplinarity achieved.
(e) Balance between basic and applied orientations and among different classes of materials.
(f) Balance between individual idea-pursuit and work on coherent areas.

In addition to evaluating the center as an organization for research, the question of the effectiveness of the block-grant mechanism of funding requires attention. That the potential benefits of block funding fall into two categories may not have been clearly recognized:

Benefits automatically accrued:

(a) Longevity. Stability of research planning, hence ability to tackle long-range, more basic problems.
(b) Creativity. Major savings of faculty time in not writing proposals and in minimizing related administration.
(c) Flexibility. Availability of funds to get new faculty going, for acquisition of major pieces of new instrumentation, starting new areas as the ideas arise, etc.

Benefits which may be achieved:

(a) Genuine Interdisciplinarity. Can be developed by propinquity, joint research programs, writing of joint papers, etc
(b) Coherent Programs. Focused research is made possible on larger and applied problems.
(c) Central Facilities. Major equipment items and services can be developed and utilized by large numbers of faculty from different departments.

When evaluated against these criteria, it is seen that the main areas where the materials center concept can be regarded as successful include:

- It drew attention to the emergence of coupled materials science and engineering as a new interdisciplinary focus of activity in a way which could not have been achieved otherwise: the development on several campuses of a true intellectual center of materials research, with a building, central facilities, key faculty members and their graduate students interacting with each other, and (occasionally) with government and industry. These institutions now constitute a national resource of vast importance.
- It demonstrated that block funding is perfectly feasible on a campus.
- The support led to several excellent research groupings of faculty members, the building-up of a reputation and attraction for good students, and the training of first-rate materials scientists, physicists, chemists, and other professionals.
- Another unique benefit was in efficiency through faculty saving their time in writing proposals and seeking support, and the agency officials likewise saving a great deal of administrative time.

- A large number of students were trained in an excellent environment for advanced degrees.

Conversely, criticisms or questions about the materials-center programs arise with respect to the following:

- Why is there so little evidence for the special impact of a $25–30 million/year program on advanced-degree production? The increase in the materials degrees shows no evidence that this increase was any more than the normal growth curve of U.S. science.
- The development of any special administrative mechanism for centralization or other effective sharing of facilities, etc., is not particularly marked in at least half of the centers.
- The dollar support associated with the output of research (publications) and with numbers of advanced degrees show a large variability. Allowing for all the factors which might affect these values, changes neither the fact nor the magnitude of the wide range in cost at universities which are otherwise very similar. Whether the differences are attributable to particular management or accounting patterns, or actually to more effective work, merits attention, if the universities are to make best use of their resources in the future.
- The degree of interdisciplinarity has developed only modestly compared with industry, although better than in the traditional departments. Coherent-area research was almost non-existent up to the date of the COSMAT survey (1971).

Taking into account the fact that the block funding of materials centers included many schools with the best faculty and reputations, the question that recurs is: “What was achieved by block funding for the materials centers that would not have been achieved by funding the faculty directly?” Specific points that raise this question are:

(a) There is little or no correlation between magnitude of block funding and development of the institution as a “materials school.” (i.e., a university with an excellent physics department receiving a block grant for materials research would have been expected to acquire some “materials” reputation <u>outside</u> of physics.)
(b) There is only modest correlation between the availability of block funding and the existence of specialized laboratory buildings, or central facilities, or their scale.
(c) There is a negative correlation between existence of block funding and interaction with industry.

(d) There is no correlation between large block grants and degree of interdisciplinary interaction.

(e) Excellence was achieved at many of the block-funded centers in the very same areas, while other important areas were neglected. For example, all the major polymer-research centers came into existence outside the block-funded schools.

On the question of what has been achieved by block funding which could not have been achieved otherwise, one of the most significant management developments has been the parallel emergence of strong university groups without the benefit of block funding; that is, the entree of block funding stimulated equivalent efforts without block funding. Case studies of such experiences might tell even more about the requirements for effective interdisciplinary work on campus.

During the 1960’s there was a rapid coalescence of the materials field, so that what were separate degree programs in metallurgy, ceramics, and, to a lesser extent, polymer science, were being brought together both by the logic of a common science of materials and by administrative fiat. Yet, while there has been a great deal of discussion about the development of “materials science” degrees, the changes have been evolutionary rather than revolutionary. A total of only ten departments call themselves “materials science and/or engineering” without a qualifier. This includes no more than 4 or 5 entirely new Ph.D. degree programs in what may be called materials science, and only one or two of those have produced any appreciable numbers of Ph.D.’s. Many of the major metallurgy departments have introduced solid-state subject matter and have adopted the title (substituting or adding) “materials science.” However, rarely does the degree program provide much exposure to ceramics or polymers, or new conceptual frameworks, or applied courses dealing with several classes of materials. This appears to be due, at least in some measure, to the fact that the educational programs themselves have not been supported by federal funding but simply reflect the existing departmental structures or new research emphases. Private institutions have not fared significantly better than their public counterparts in this respect.

There is still some question as to whether or not a new academic discipline of materials science or of materials engineering will emerge. An unresolved issue on this point is the extent to which polymer science can be integrated into the rest of materials science. There is as yet no example of a well-known polymer-oriented Ph.D. curriculum sharing a basic core with other materials science students. Either such a new materials discipline with metallurgy, ceramics, and polymer science becoming branches or subfields within it (more or less like chemistry and its division into physical, inorganic, organic, etc.) will develop, or increasingly what may appear is a group of materials sciences affiliated loosely with each other. Indeed, the solution presently adopted by some of the largest departments points in the latter direction. These departments may offer three or four options in ceramics, metals, polymers, and a more basic undifferentiated materials science, which is an arrangement that allows a degree of specialization but simultaneously provides a common foundation. At present, there are real difficulties in achieving genuine intellectual innovation on curricular matters against the "interests" of existing departments. It should be noted that the same problem exists in Europe, and the most integrated materials-degree programs have emerged in the newer universities. Evidently, committed support for those capable institutions willing to try appears to be a necessity if serious curricular experiments are to be undertaken.

At present, the curriculum emphasis in many materials-designated departments is overweighted in the direction of:

- science, at the expense of engineering;
- physics, at the expense of chemistry;
- materials structure and properties, at the expense of materials processing and systems;
- metals, at the expense of ceramics and polymers.

An attempt has been made to provide an estimate of the relative strengths of graduate programs in the materials-designated departments. It is worth noting that, among the ten departments identified as the strongest, a high proportion have moved far towards incorporating the new materials science unifying theme. In addition, a very few exceptional, though small, departments exist. From the point of view of quality, however, it appears that a large percentage of the graduate programs are not outstanding.

The number of materials-designated departments is high in relation to total student enrollment and resources available or likely. Most indicators at the graduate level suggest that size of programs is strongly correlated with quality. By such criteria, the majority of materials departments are too small. A faculty of less than ten and a graduate student body of less than 30, or a Ph.D. production below 5/yr. seems to be too small to guarantee high quality work (allowing for exceptional cases, of course). Yet, less than twenty institutions reach this level among the materials-designated departments. Small undergraduate departments or materials sections of larger departmental conglomerates, on the other hand, may be justified since they are needed to provide the essential materials component of engineering curricula.

In the curricula of departments relevant to materials, materials science seems to have had very little influence. Yet it is clear that materials science is a very pervasive theme in perhaps half of modern industrial technology. Chemistry and physics departments have provided (and undoubtedly, will continue to do so) the basic sciences on which advanced materials education is built, and graduates in the basic sciences will also play a key role in the total materials research picture. However, considering the fact that graduates of these classical fields will work increasingly in industries with activities focused around the materials theme, it would seem wise to give such science students a formal exposure to materials-science or solid-state courses. In the future, it is probable that the national trend towards more application for physics and chemistry will rapidly accelerate the need for vigorous interaction between the science departments and the materials-designated departments in curricular matters.

A very significant impact of the materials research expansion at universities has been on the basic science departments of physics and chemistry. The growth in sophistication of equipment and in quality of faculty and research efforts (and, derivatively, the quality of the graduates) in solid-state science is in large part due to the funds made available to the science community under the rubric of "materials science." This was an understandable allocation of resources since perhaps no other single disciplinary group played a greater role in the development of the underlying, unifying principles. However, a decade later, there is a general consensus within that community that the success of solid-state physics has been so substantial that much of the intellectual challenge has been met, particularly in the theoretical area. Hence, the involvement of the physics community in the materials science of the 1970's is likely to be quite different. There is no lack of challenge in the more applied aspects of the field, i.e. the application of the very principles discovered earlier. This shift of the center of gravity of the physics interest towards such applied work is likely to be accomplished only by a much greater degree of cooperation and interdisciplinarity with the materials-designated and other engineering departments. (Comments were made earlier on the need for broader instruction of the physics student in materials science.)

The chemistry departments reflect a somewhat different situation in that chemistry has been less influential in the materials field. However, there is an increasing awareness in chemistry departments of both the inorganic solid state and of the materials aspects of polymerics. Here again, as the chemical-synthesis phase of polymer research has reached its zenith, the chemist will need to interact more vigorously than in the past with colleagues in materials science and physics if the necessary research challenges are to be met effectively and vigorously.

In the case of the engineering departments, it was noted earlier that the materials-designated departments themselves constitute (probably with physics) the largest departmental units in materials research. The most important development within such departments is that they are becoming more interdisciplinary within themselves—by taking on physicists, electrical engineers, chemical engineers, etc., both as faculty members and as graduate students. While this is desirable, it is equally important for continued cross-fertilization that such departments keep open their working connections to both science and engineering colleagues in other departments. Where a center exists, there is a logical venue for such cooperation in research; where it does not, ad-hoc group research involving interdisciplinary teams may need special encouragement. The decision made by departments to preserve distinct identity-oriented specializations is also wise. The 1970's will demand a definite increase in the engineering or "experience-intensive" materials fields, from extractive metallurgy to materials for specific applications. Active research programs in ceramic engineering, polymer engineering, and process metallurgy will deserve emphasis.

Of the other engineering departments, it was indicated previously that electrical engineering involvement in materials research appears to be decreasing. In contrast, chemical engineering is developing interests in materials research as emphasis moves towards processing systems. Likewise, because of the demands of public technology (in road building, solid-waste disposal, general construction), the interaction between the materials and civil engineers is likely to increase substantially.

MATERIALS MANPOWER AND PROFESSIONAL ACTIVITIES

It is evident from the foregoing sections that the field of materials science and engineering is very diverse. Correspondingly, scientists as well as engineers in the field are drawn from many disciplines. As a group, their activities must range over a wide spectrum, including:

- the manufacture or production of materials
- the chemical and physical properties of materials
- the mechanical or engineering properties of materials
- the processing of materials into finished goods or articles
- the end conditions or applications for which materials are used
- the disposal and recycling of materials
- the economics of materials from manufacture through end-use, disposal, and recycling.

Likewise, they are employed in a variety of sectors and institutions—in private industry, colleges and universities, government, and nonprofit institutions.

In this section of Chapter 7, attention is directed to the numbers, character, and origin of the professional manpower in the field, and to the nature of the professional societies and activities associated with it. Such features define what can usefully be considered as the “materials community.”

Materials Manpower

At the outset it should be recognized that by no means all scientists and engineers working on problems of materials received professional training in materials, i.e. a materials-designated degree. In fact, the statistics show that the majority of professionals working on materials hold degrees in virtually all areas of the physical sciences and engineering, and that materials-designated degree- holders—metallurgists, ceramists, and polymer engineers —represent only a small fraction of the total professional manpower working in the materials field.

MSE is so diverse and so broad that accurate data about personnel in the field is difficult to obtain. The problem is compounded by the facts that the machine-readable National Registers of professional personnel maintained by the National Science Foundation for scientists were compiled only in the four years 1964, 1966, 1968, and 1970, and that only one national survey of engineers (for the year 1969) has ever been made. Moreover, the National Registers were not designed to separate data pertaining to MSE and it has been necessary to develop a method to do so. The first step, the selection of the disciplines of science and fields of specialization of engineering encompassed by MSE was based on the process described in detail in Chapter 2, *whereby categories used in the National Engineers Register and the National Register of Scientific Personnel were identified by the collective judgment of about 150 professionals in industry, education, and government.

With the categories of MSE thus selected, the computer storage data banks of the National Registers were used to obtain statistical information about the manpower in the field. However, it should be noted that the Registers do not include all the professionals in the U.S. —the Engineers Register for 1969 totaled only 308,000 or 30.8%, out of an estimated 1,000,000 engineers working in the U.S., and the Scientific Personnel Register totaled 298,000 or 64.8%, out of an estimated 460,000. (The Register data are restricted to members of the various relevant technical societies.) Accordingly, the statistics obtained from the National Registers and reported here, have been adjusted to given an estimated total number in each category.

The resulting data on the number of professionals working in various categories of engineering and science as embodied in MSE are given in Tables 7.46 and 7.47.[19] A significant characteristic of the engineering data is that it would seem that more engineers are working on materials in the category called structural than in any other. (The category "structural" includes engineers concerned with structures, concrete technology, and rock mechanics.) It is also noteworthy that the "electromagnetic" category also has a large number of engineers working on materials—about as many as metallurgical. The data in Table 7.47 show that the number of scientists working in the field of metallurgy is only 2.7% of the total scientists in materials. This percentage seems abnormally low because metallurgy tends to be thought of as a science rather than an engineering discipline. However, this low percentage may be attributed to the fact that Tables 7.46 and 7.47 are based on the data from the National Registers of Engineers and Scientists, which in turn are based on society membership. Most metallurgists during their professional career join the American Society for Metals or The American Institute of Mining, Metallurgical and Petroleum Engineers, and data on the membership of these societies are reported through the National Register for Engineers. Therefore, most of the metallurgists are shown in Table 7.46 as materials engineers rather than in Table 7.47. Among the scientific disciplines embodying materials, that of organic chemistry is by far the largest, accounting for 31.6% of the total. In fact, the various disciplines of chemistry as a group dominate the scientists working in materials—76.6% of such scientists are in chemistry.

All told in the years 1968–69, there were about 360,000 scientists and engineers working on materials in the U.S. These professionals in the field of MSE provided the technical base for an estimated employment of at least sixteen million people, both blue collar and white collar engaged in the production of materials, i.e., in the selected categories of the "durable and

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* Chapter 2, Volume I, of this Series.

[19] National Engineers Register 1969 and the National Register of Scientific and Technical Personnel 1964, 1966, 1968, and 1970.

TABLE 7.46 Estimated Number of Engineers Working in Materials Science and Engineering in 1969 (By Fields of Specialization)*

Category of Engineering	Number	% of Total
Structural	48,000	16.2
Concrete Technology		
Structures		
Rock Mechanics		
Metallurgical	41,000	13.8
Metallurgy, general		
Metallurgy, physical		
Metallurgy, powder		
Metallurgy, process		
Metallurgy, extractive		
Casting		
Welding		
Beneficiation, ore processing		
Electromagnetic	39,000	13.2
Dielectrics		
Magnetics, Magnetism		
Insulation, Electrical		
Superconductivity		
Photoelectricity		
Electronic Application		
Electrical Application		
Chemical	37,000	12.4
Materials Properties		
Crystal, Crystallography		
Materials Applications		
Corrosion		
Coating, Plating, Cladding		
Filament Technology		
Thermochemistry		
Electrochemistry		
Fuel Cells		
Chemical Applications		

* Data derived from the National Engineers Register.

Category of Engineering	Number	% of Total
Work Management and Evaluation	34,000	11.5
Nondestructive Tests		
Testing, Laboratory		
Radiography, X-rays		
SpecificaStandards		
Product Engineering		
Production Methods		
Quality Control		
Dynamics and Mechanics	30,000	10.1
Friction		
High Pressure		
Lubrication		
Vacuum Technology		
Kinetics		
Mechanical Applications		
Mechanics		
Mass Transfer		
Propulsion		
Engineering Process and Application	21,000	7.1
Forming, Shaping		
Fastening, Joining		
Materials Handling		
Refining		
Processes		
Heat, Light, and Applied Physics	21,000	7.1
Solid State		
Thermodynamics		
Insulation, Thermal		
Thermophysics		
High Temperature		
Physics		
Applied Physics		
Cryogenics		
Ultrasonics		
Heat Transfer		
Automation and Control Instrumentation	18,000	6.1
Information, Mathematics	7,000	2.4
Environmental	300	0.1
	296,300	100.0%

TABLE 7.47 Estimated Number of Scientists in Materials Science and Engineering in 1968 (By Fields of Specialization)*

Field of Specialization	Number	% of Total
Organic Chemistry	20,000	31.6
Physical Chemistry	9,900	15.6
Analytical Chemistry	7,700	12.1
Inorganic Chemistry	5,100	8.0
Other in Related Chemical Specialties	4,200	6.6
Metallurgy and Materials	1,700	2.7
		76.6%
Solid State	5,800	9.1
Atomic and Molecular	1,900	3.0
Optics	1,600	2.5
Other Physics Specialties	1,300	2.1
Electronics	800	1.3
Electromagnetism	700	1.1
Thermal	700	1.1
Nuclear	600	0.9
Mechanics	400	0.6
Fluids	200	0.3
Acoustics	100	0.2
		22.2%
Geology	500	0.8
Geochemistry	100	0.2
Solid Earth Geophysics	100	0.2
		1.2%
	63,400	100.0%

* Data derived from the National Science Register.

and nondurable" goods sectors of U.S. manufacturing industry as shown in Table 7.48.[20]

The characteristic profile of professional manpower in MSE can be derived from the data in the National Registers. Taking first the scientists and engineers in the field who appear in the National Engineers Register, the situation in 1969 is shown in Table 7.49. Even more extensive information about such materials professionals could have been extracted from 1969 National Engineers Register, but the information in the table suffices to illustrate the diversity of the field. Unfortunately, it was not possible to obtain trends over time, and hence extrapolate into the future, because the Engineers Register was made only once in detailed and analyzable form. For such reasons, it would be worthwhile to have a National Register of Engineers made at least every five years and preferably every two years.

Turning to the materials professionals appearing in the National Science Registers, which were made every two years from 1964 to 1970, a corresponding profile can be drawn and some trends discerned. Tables 7.50, 7.51, and 7.52 indicate that for the scientists working in the field of materials, there was over the period 1964–1970:

- an increase in the percentage working in basic research,
- an increase in the percentage working in development and design,
- a slight decrease in the percentage who were teaching,
- an increase in the percentage working in colleges or universities,
- a decrease in the percentage working in private industry, and
- a strong decrease in the number and percent of the total number 25 years and younger.

The last of these points may be attributed to the drop in the last few years of students electing chemistry as a major and to the aging of the total population of chemists. Such aging is evident from the constancy in the last four Registers of the total number of chemists in materials, coupled with the fewer chemists entering the field of chemistry. Whether the various trends indicated above persisted during the economic recession in 1970 and 1971 is not known.

A group of scientists and engineers in materials which merits special note is that working in the area of synthetic polymers in materials (macromolecules) —plastics, rubbers, and synthetic fibers. This area is the family of new materials which has grown to major importance in the last two decades. The growth of employment, both blue collar and white collar, in this field of plastics as reported by the Department of Labor under chemicals[21]

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[20] "Labor Force Employment and Earnings," Survey of Current Business (November 1971) S-13.

[21] "Employees in Manufacturing of Durable and Nondurable Goods," Statistical Abstracts of the United States (1959–1971).

TABLE 7.48 Total Employment (Both Blue Collar and White Collar) in U.S. Materials and Related Industries Served by the Professionals Working in the Field of Materials Science and Engineering, 1970

Manufacturing	NumberPersons
Nondurable Goods	
Plastics Materials and Synthetics	224,000
Textile Mill Products	1,002,000
Apparel and other Fabricated Textile Products	1,409,000
Paper and Allied Products	711,000
Rubber and Miscellaneous Plastic Products	596,000
Leather and Leather Products	343,000
Durable Goods	
Ordnance and Accessories	316,000
Lumber & Wood Products, Except Furniture	607,000
Furniture and Fixtures	484,000
Stone, Clay, and Glass Products	656,000
Primary Metal Industries	1,361,000
Fabricated Metal Products	1,440,000
Machinery, Except Electrical	2,003,000
Electrical Machinery	2,020,000
Transportation Equipment	2,060,000
Instruments	477,000
Miscellaneous Manufacturing Industries	441,000
	16,150,000

TABLE 7.49 Profile of Materials Scientists and Engineers Appearing in the National Engineers Register in 1969

Sex	Male	99.6%
Female	0.4%	
Unemployed or employed part time:		2.2% of non Ph.D.'s
	1.7% of Ph.D.'s	
College Degree:	B.S.	53.5%
M.S.	21.9%	
Ph.D.	11.2%	
No report	4.6%	
No degree or no acceptable degree	4.3%	
Professional	3.2%	
Associate	1.0%	
Foreign	0.4%	
Major college curriculum:	Mechanical	16.9%
Civil	14.0%	
Chemical	12.6%	
Metallurgical	9.7%	
Electrical	7.7%	
Electronic	4.2%	
Aero	2.8%	
Eng. Mech.	2.7%	
Bus. Adm.	2.6%	
Physics	2.2%	
Chemistry	1.9%	

	Industrial	1.4%
Agricultural	1.4%	
Petroleum	1.0%	
Materials	0.6%	
All others (23 categories)	18.3%	
Country of Highest Degree:	USA	90.5%
All others (38 countries)	7.9%	
England	0.7%	
Canada	0.5%	
Germany	0.4%	
Professional Identification:	Engineer	73.9%
Other	14.1%	
Metallurgist	7.0%	
Technician	1.8%	
Chemist	1.5%	
Physicist	1.3%	
Mathematician	0.4%	
Type of Employer:	Private Ind.	77.4%
College & Univ.	7.8%	
Gov. (Fed. State & Local)	7.0%	
Self-employed	0.6%	
Military	0.6%	
Other	3.4%	

Government Support:	None	59.1%
Don't Know	3.8%	
Yes	37.1%	
Source:		
Defense	56.3%	
Space	25.1%	
Atomic Energy	14.6%	
Transportation	13.3%	
Public Works	9.3%	
Education	7.9%	
Health	5.1%	
Housing	4.1%	
Natural Resources	4.1%	
Urban Development	2.9%	
Agriculture	2.3%	
International	1.6%	
Employment Function:	Design	17.4%
Planning, directing	13.9%	
Research	11.2%	
Development	10.8%	
Sales, Tech. Serv.	10.5%	
Advisory, consulting	7.8%	
Production	6.7%	
Teaching, training	5.5%	

	Other	4.0%
Testing, eval.	3.6%	
Construction	3.3%	
Quality Assm.	2.6%	
Coordination	1.8%	
Purchasing	0.9%	
Supervisory Function:	None	20.9%
Project or Section	19.7%	
Major dept. div.	18.3%	
Indirect, Staff	16.9%	
Team or unit	11.7%	
Gen. management	9.6%	
No report	3.0%	

TABLE 7.50 Distribution of Materials Scientists by Employment Function

	Percentages by Years			
Employment Function	1964	1966	1968	1970
Basic Research	21.0	20.1	23.8	22.6
Applied Research	19.0	16.8	17.9	18.8
Development and Design	13.6	14.5	16.2	15.0
Teaching	10.2	10.4	8.7	9.4
Management, R&D	14.2	13.2	14.0	14.0
Management, Other	5.8	5.9	6.6	6.7
Other	8.5	7.5	7.2	6.6
No report	7.6	11.7	5.6	6.7
Total	100.0	100.0	100.0	100.0
	(65,000)	(66,100)	(65,700)	(63,400)

TABLE 7.51 Distribution of Materials Scientists by Type of Employer

	Percentages by Years			
Type of Employer	1964	1966	1968	1970
Private Industry, Business	60.0	57.7	60.9	58.6
College or University	20.1	20.7	22.3	23.3
U.S. Government	6.2	6.0	6.1	6.3
Non-Profit Organization	1.7	1.7	1.7	1.4
Research Center	2.5	2.1	2.5	1.7
Other	4.1	3.7	3.0	3.4
No Report	5.4	8.1	3.5	5.3
Total	100.0	100.0	100.0	100.0

TABLE 7.52 Distribution of Materials Scientists by Age Grouping

	Percentages by Years			
Age Grouping	1964	1966	1968	1970
Under 25	6.3	6.2	5.0	3.7
25–29	17.6	18.2	19.7	19.9
30–34	17.1	15.9	16.5	18.0
35–39	16.6	16.0	14.6	13.6
40–44	14.9	13.7	13.4	13.2
45–49	10.7	11.7	12.0	11.8
50–54	7.3	7.9	8.7	8.9
55–59	4.5	4.8	5.2	5.8
60–64	2.8	2.8	3.0	3.0
65–69	1.4	1.5	1.2	1.2
Over 69	0.8	1.0	0.5	0.6
No Report	0.0	0.3	0.2	0.3
Total	100.0	100.0	100.0	100.0

is shown in Figure 7.45. This growth amounted to about 85% for the period 1958–1970, whereas the growth in total employment in the U.S. was about 24% for the same period of time. The professional manpower working in the plastics field includes 19,000 chemists[22] and 16,700 plastic engineers. These data were obtained from the National Register of Scientists for 1970 plus an adjustment for the total number of chemists employed in the U.S., and from the 1971 membership of the Society of Plastics Engineers. A further indication of the rapid growth in the area of macromolecules is apparent from the growth of membership[23] in the Society of Plastics Engineers for the period 1957–1971, shown in Figure 7.46.

As a final point in this profile of professionals in the field of MSE, it is instructive to examine the mix of disciplinary backgrounds among professionals in relevant industrial laboratories. Eight large laboratories in six industries which are concerned to a major degree with R&D on materials and materials-related problems were surveyed to determine the mix of disciplines employed in their laboratories. Each laboratory listed its researchers by discipline and by age group. The results, given in percentages, are shown by industry in Table 7.53. From these limited data, it can be tentatively concluded that:

- Most of the laboratories have people with different disciplines rather than people with materials training as such.
- For the six industries surveyed in this way, 14% of the researchers were from the disciplines of materials, metallurgy, ceramics, and mineralogy.
- Chemistry, chemical engineering, organic chemistry, life sciences, and fuel engineering were disciplines with the largest overall representation.
- In the electronics industry, much of the materials-oriented work in R&D associated with new electronic components and integrated circuits is carried out by professionals formally trained in physics and electrical engineering, rather than in materials per se.
- Materials, metallurgy, ceramics, and mineralogy account for 37% of the disciplines of research personnel in the steel industry.

Turning now to the question of the flow of manpower from the universities into the professional materials community discussed above, we shall first examine the statistics on materials-designated degrees at the baccalaureate and graduate level. Holders of such degrees—which include metallurgy, ceramics, polymer science, or materials science and engineering

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[22] Data supplied by American Chemical Society, Washington, D.C.

[23] Data supplied by Society of Plastics Engineers, Inc., Greenwich, Conn.

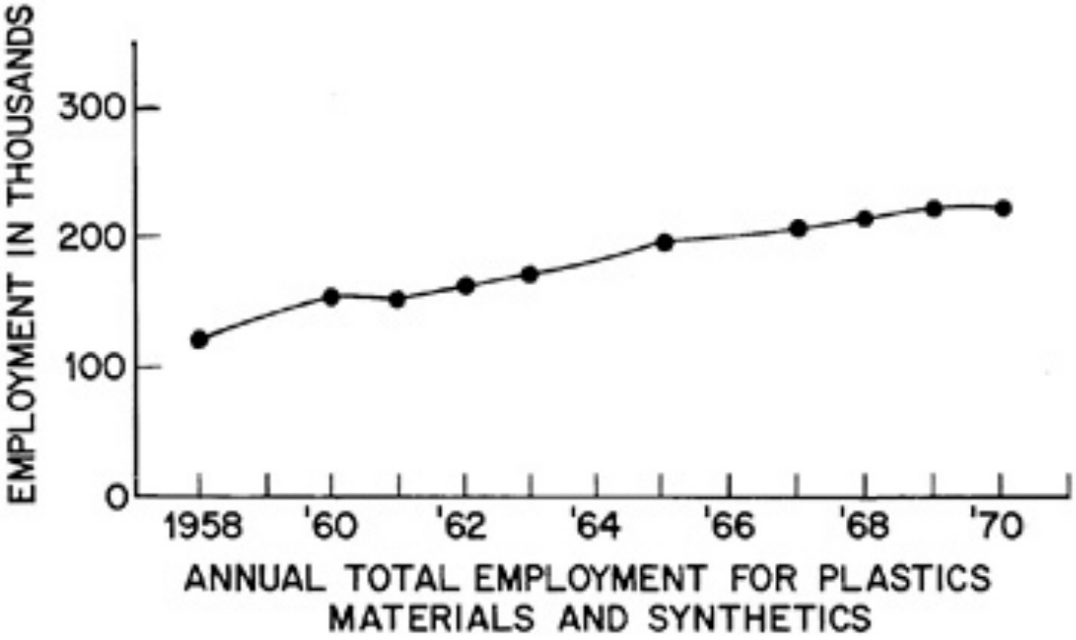
EMPLOYMENT IN THOUSANDS
300
200
100
0
1958
'60
'62
'64
'66
'68
'70
ANNUAL TOTAL EMPLOYMENT FOR PLASTICS MATERIALS AND SYNTHETICS

FIG. 7.45

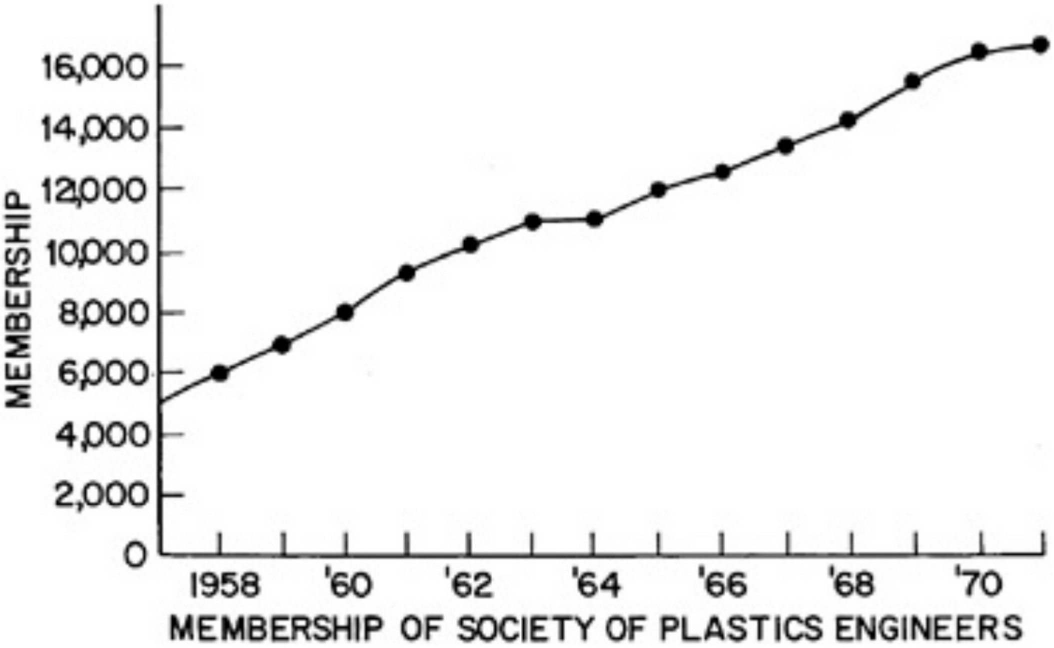
MEMBERSHIP
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
1958
'60
'62
'64
'66
'68
'70
MEMBERSHIP OF SOCIETY OF PLASTICS ENGINEERS

FIG. 7.46

TABLE 7.53 Disciplinary Mix in R&D Laboratories

Disciplines	Electronics Industry R&D**	Steel Industry R&D**	Independent Lab R&D*	Aerospace Industry R&D*	Nonferrous Industry R&D*	Glass Industry R&D*	Average for all Laboratories***
	%	%	%	%	%	%	%
Materials Metallurgy Ceramics Mineralogy	5	37	16	2	15	11	14
Physics	32	4	11	17	11	6	14
Electrical Engr. Electronics Engr.	31	5	6	21	2	–	11
Chemistry Chem. Engr. Organic Chem. Life Sciences Fuel Engr.	21	36	23	6	22	36	24
Mech. Engr. Aero. Engr. Civil Engr. Engrg. Mech. Appl. Mech. Design Engr.	4	9	19	37	3	22	16
Mathematics Statistics	3	3	4	3	–	–	2
Other	5	7	21	14	47	25	20
	101%	101%	100%	100%	100%	100%	101%

* Data from one laboratory.

** Data from two laboratories.

*** Average for all laboratories is an average of the total of the percentages for the disciplines shown.

in the degree title—constitute only a fraction, as was discussed above, of the professionals actively working on materials in industry, government, and the universities. Nevertheless, the quantities and time-trends of such degrees are important for understanding the characteristics of the field of MSE.

The collection of U.S. statistics on materials-designated degrees appears to have begun in the 1940's with metallurgy degrees through the efforts of the American Society for Metals. Subsequently, the Engineering Manpower Commission of the Engineers Joint Council and the Office of Education of the U.S. Department of Health, Education and Welfare included such degrees in their annual statistics. Thus, the category, "Metallurgical and Materials Engineering" was used for the first time in 1964–65 by the Office of Education in the collection of data on student enrollment and degrees conferred in engineering. In 1967–68, the Engineering Manpower Commission changed the category title to "Materials" which included metallurgical, materials, and ceramics curricula. (Degrees in polymer science were not included, but until very recently, the number of such degrees has been very small and almost entirely at the graduate level.)

It will be seen in Figure 7.47 that during the period 1958–1970, the number of bachelor's degrees in materials[24] has been approximately constant while the master's and doctorates conferred annually have grown steadily from 130 and 74 respectively in 1958 to 472 and 298 in 1970. In 1970, 982 bachelor's, 472 master's, and 198 doctorates in materials were conferred by the college and universities.

Comparisons of the bachelor's, master's, and doctorates conferred in materials with corresponding degrees in other selected fields in engineering are shown in Figures 7.48, 7.49, 7.50, and 7.51. Although, as noted, the master's and doctorates conferred in materials have shown a steady increase in the last 15 years, the number of these degrees is lower than in chemical, civil, mechanical, and electrical engineering. The number of bachelor's in materials conferred in 1968 was about 2.7% of the total bachelor's conferred in all fields of engineering. Correspondingly, the master's and doctorates conferred in materials in 1968 were 4.1% and 7.6% respectively of the total master's and doctorates conferred in all fields of engineering. Trends in the materials degrees as percentages of the respective degrees in engineering were discussed in connection with Figure 7.32; these percentages have been holding fairly steady for the past 10 years.

Immigration of qualified professionals from other countries appear to have been a significant factor in increasing U.S. manpower in materials. The immigration of scientists and engineers in general into the U.S. developed

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[24] Various authors of annual studies of "Total Engineering Degrees and Enrollment in Institutions with One or More ECPD —Accredited Curriculum," usually published in the February issue of Journal of Engineering Education, Individual Issues, 1935–1968.

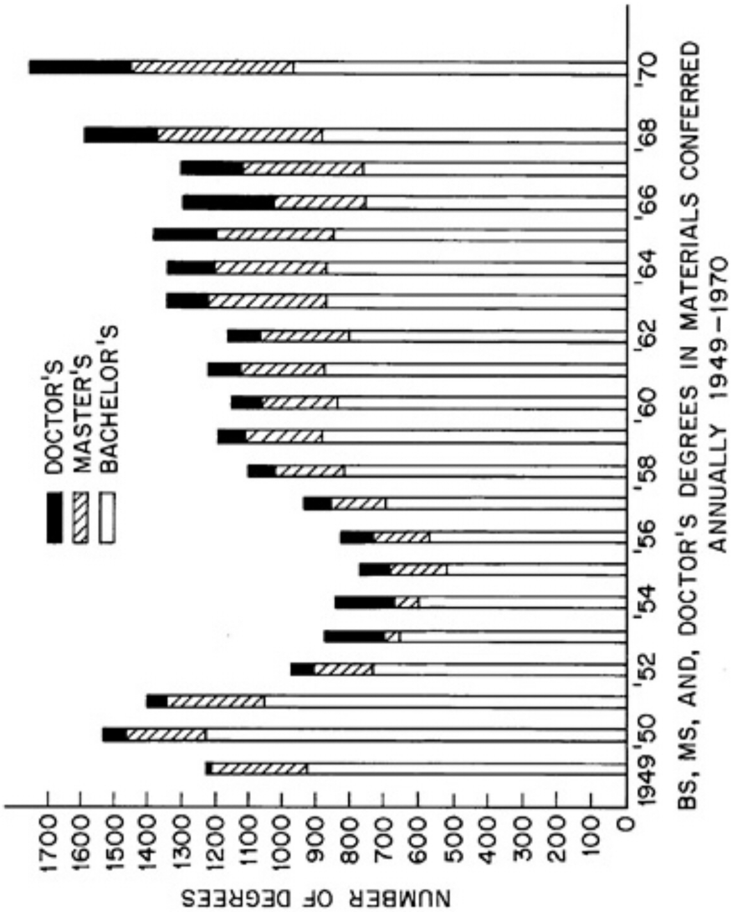
DOCTOR'S
MASTER'S
BACHELOR'S
NUMBER OF DEGREES
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1949
'50
'52
'54
'56
'58
'60
'62
'64
'66
'68
'70
BS, MS, AND, DOCTOR'S DEGREES IN MATERIALS CONFERRED
ANNUALLY 1949–1970

FIG. 7.47

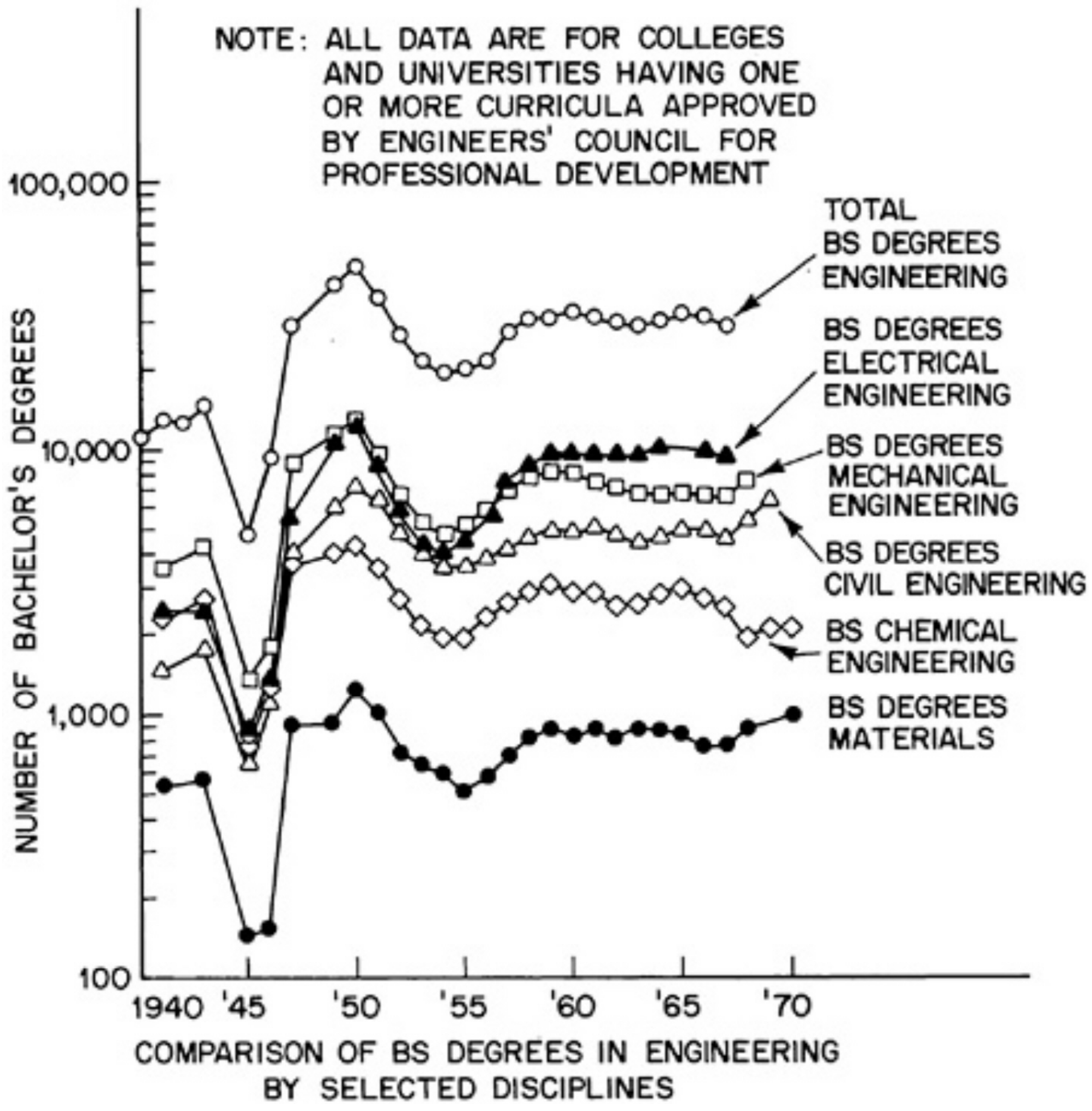
NOTE: ALL DATA ARE FOR COLLEGES AND UNIVERSITIES HAVING ONE OR MORE CURRICULA APPROVED BY ENGINEERS' COUNCIL FOR PROFESSIONAL DEVELOPMENT
TOTAL BS DEGREES ENGINEERING
BS DEGREES ELECTRICAL ENGINEERING
BS DEGREES MECHANICAL ENGINEERING
BS DEGREES CIVIL ENGINEERING
BS CHEMICAL ENGINEERING
BS DEGREES MATERIALS
NUMBER OF BACHELOR'S DEGREES
100,000
10,000
1,000
100
1940
'45
'50
'55
'60
'65
'70
COMPARISON OF BS DEGREES IN ENGINEERING BY SELECTED DISCIPLINES

FIG. 7.48

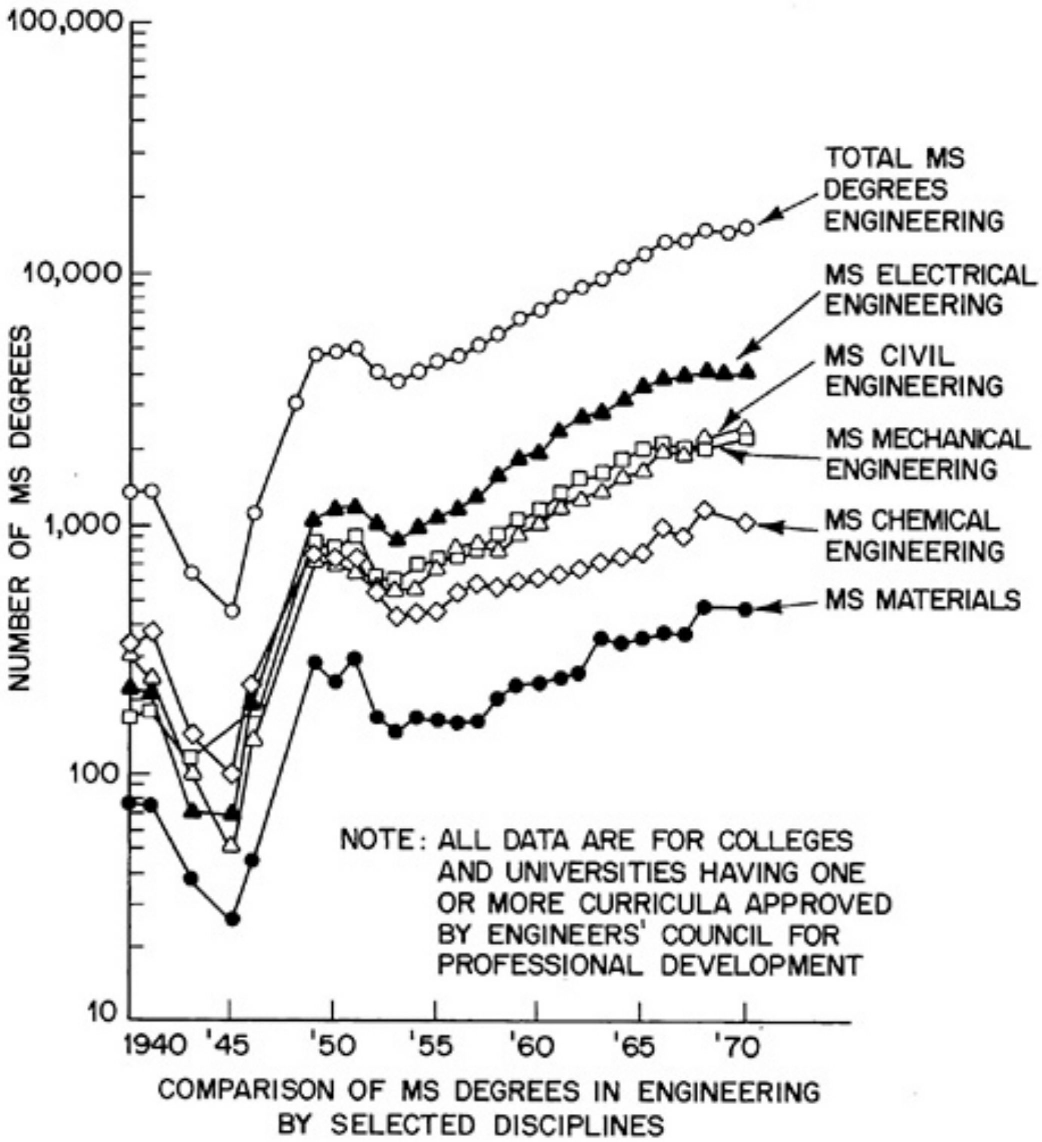
100,000
10,000
1,000
100
10
NUMBER OF MS DEGREES
1940
'45
'50
'55
'60
'65
'70
TOTAL MS DEGREES ENGINEERING
MS ELECTRICAL ENGINEERING
MS CIVIL ENGINEERING
MS MECHANICAL ENGINEERING
MS CHEMICAL ENGINEERING
MS MATERIALS
NOTE: ALL DATA ARE FOR COLLEGES AND UNIVERSITIES HAVING ONE OR MORE CURRICULA APPROVED BY ENGINEERS' COUNCIL FOR PROFESSIONAL DEVELOPMENT
COMPARISON OF MS DEGREES IN ENGINEERING BY SELECTED DISCIPLINES

FIG. 7.49

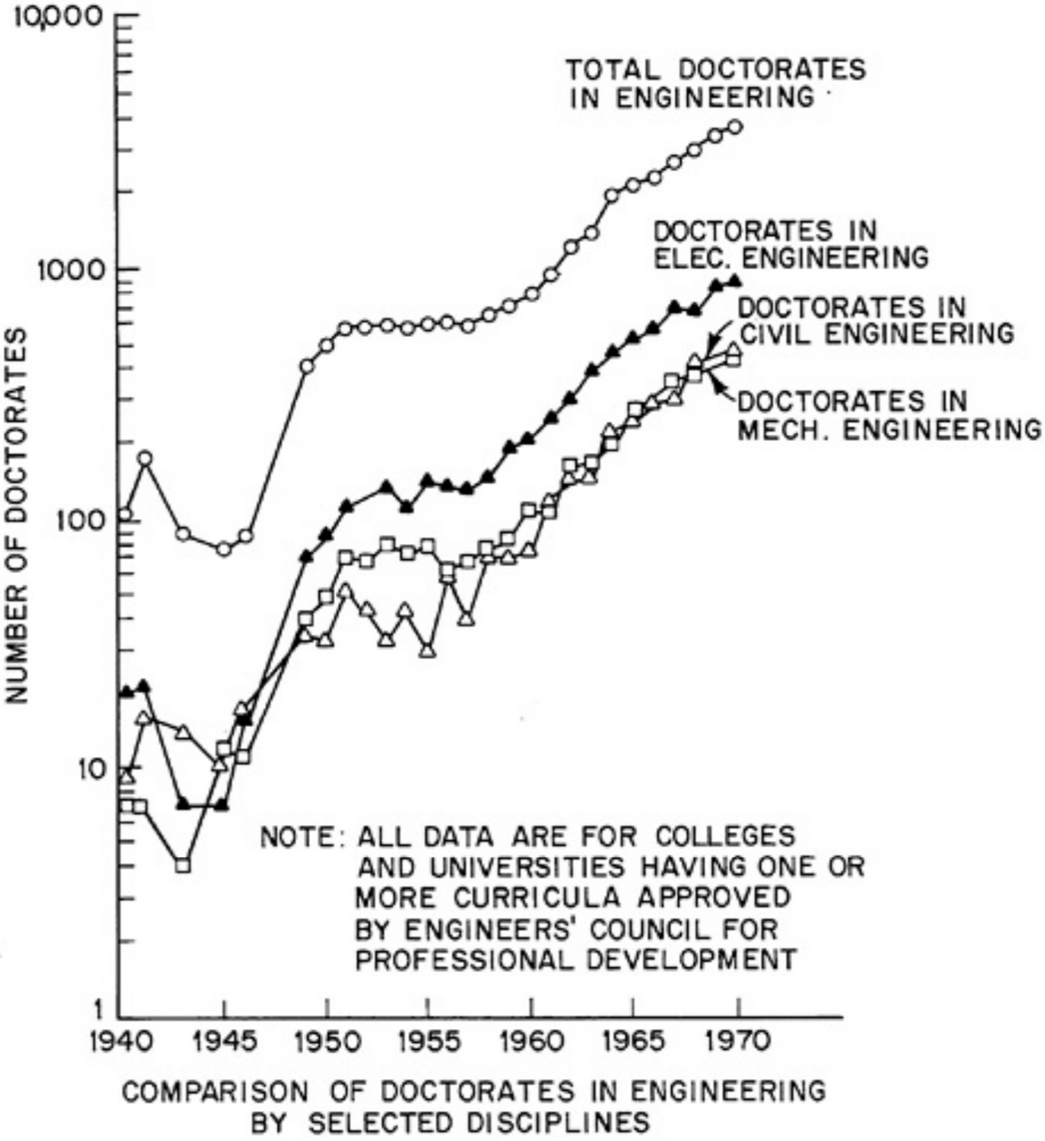
10,000
1000
100
10
1
NUMBER OF DOCTORATES
TOTAL DOCTORATES IN ENGINEERING
DOCTORATES IN ELEC. ENGINEERING
DOCTORATES IN CIVIL ENGINEERING
DOCTORATES IN MECH. ENGINEERING
NOTE: ALL DATA ARE FOR COLLEGES AND UNIVERSITIES HAVING ONE OR MORE CURRICULA APPROVED BY ENGINEERS' COUNCIL FOR PROFESSIONAL DEVELOPMENT
1940
1945
1950
1955
1960
1965
1970
COMPARISON OF DOCTORATES IN ENGINEERING BY SELECTED DISCIPLINES

FIG. 7.50

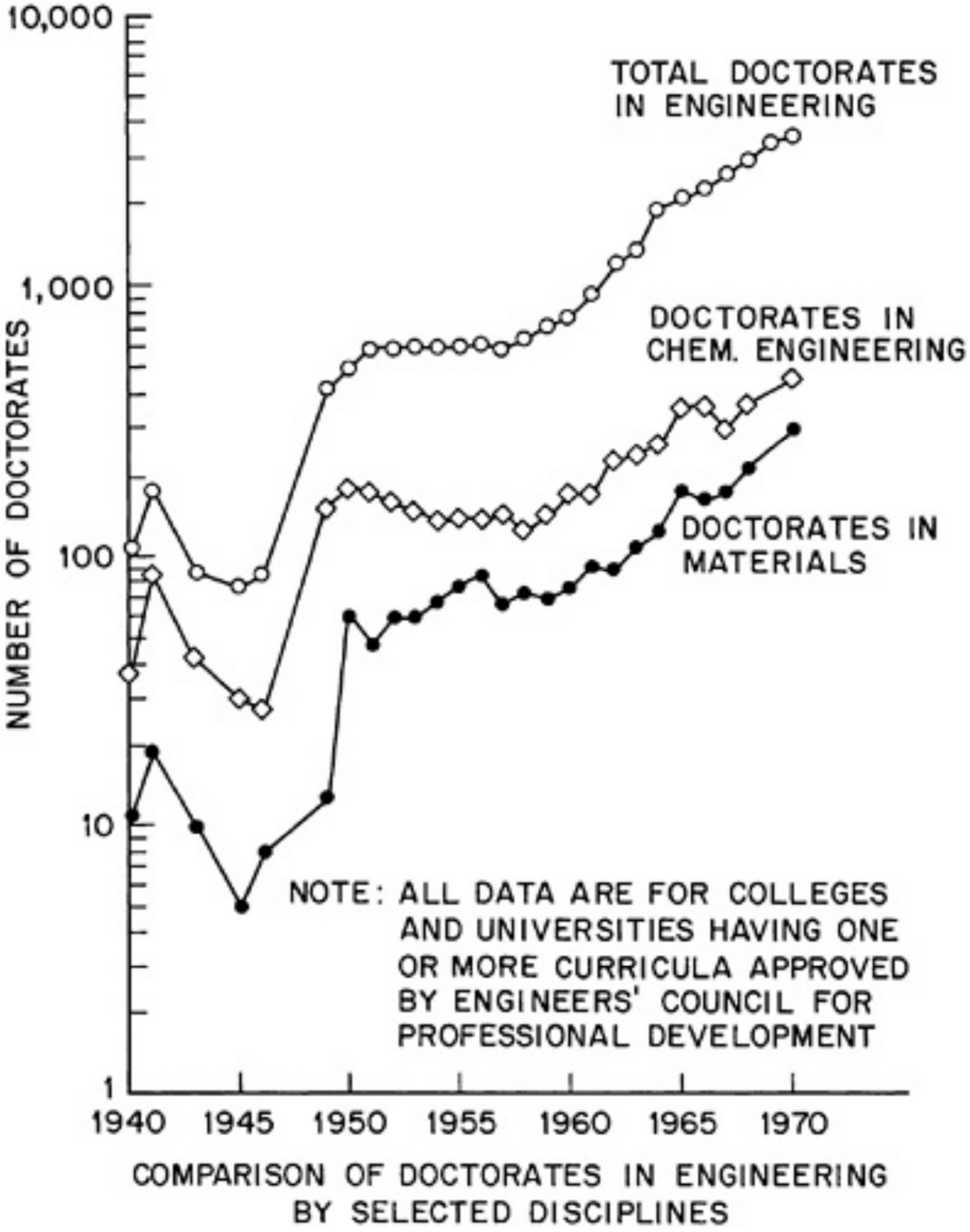
10,000
1,000
100
10
1
NUMBER OF DOCTORATES
TOTAL DOCTORATES IN ENGINEERING
DOCTORATES IN CHEM. ENGINEERING
DOCTORATES IN MATERIALS
NOTE: ALL DATA ARE FOR COLLEGES AND UNIVERSITIES HAVING ONE OR MORE CURRICULA APPROVED BY ENGINEERS' COUNCIL FOR PROFESSIONAL DEVELOPMENT
1940
1945
1950
1955
1960
1965
1970
COMPARISON OF DOCTORATES IN ENGINEERING BY SELECTED DISCIPLINES

FIG. 7.51

developed into a substantial source of such professional manpower during the period 1950–1970. In 1970, 9305 engineers and 3264 natural scientists immigrated into the U.S. Among the natural scientists were 380 agricultural scientists, 388 biologists, 1495 chemists, 162 geologists and geophysicists, 348 mathematicians, 401 physicists, and 90 other natural scientists. Among the engineers were 105 aeronautical, 908 chemical, 1509 civil, 1464 electrical, 356 industrial, 1618 mechanical, 160 metallurgical, 59 mining, 63 sales, and 3063 other engineering.[25] It is reasonable to assume, based on the data obtained from the National Registers, that about 30% of the engineers and about 14% of the natural scientists who immigrated to the U.S. took jobs in some area of MSE. The increase of immigration of engineers and natural scientists for 1970 over 1969 was about 29%. The 9305 immigrant engineers in 1970 represented about 18% of the total bachelor's, master's, and doctor's degrees in engineering conferred in the U.S. in that year.

The immigration of metallurgists, natural scientists, and engineers for the period 1949–1970[25,26,27] is shown in Figure 7.52. During this period of 21 years, a total of 118,345 engineers and natural scientists immigrated into the U.S. This number is about 9% of the total degrees awarded in engineering and the physical sciences in the U.S. in that same period of time.

For the period 1952–1968, immigration into the U.S. was on a national quota system.[25] At the end of fiscal year 1968, immigration from both hemispheres proceeded on a first-come, first-served basis, with the inflow from the Eastern Hemisphere limited to 170,000 yearly (20,000 maximum from any country), and from the Western Hemisphere limited to 120,000 yearly as a whole. By definition the Western Hemisphere contains North, Central, and South America. The Eastern Hemisphere is the remainder of the world.

According to the National Science Foundation, "As of February 4, 1971, the U.S. Department of Labor revised its procedure for certifying the immigration of scientists and engineers. After that date, such immigrants entering the U.S. under occupational preferences must have a job offer for which domestic workers are not readily available, and their employment must not adversely affect the wages and working conditions of indigenous workers similarly employed in the area of intended employment. As a result, future inflows of scientists and engineers from abroad will probably more closely reflect the demand for such personnel than occurred in the recent past."

Details on the emigration of scientists and engineers from the U.S. to other countries are not available. Beginning in 1969, the State Department began to maintain records on the number of people who apply for passports to

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[25] "Immigrant Scientists, Engineers, and Physicians Increase in FY1970," Science Resources Studies Highlights, National Science Foundation, NSF-71–11, April 22, 1971.

[26] "Scientific Manpower from Abroad," National Science Foundation, NSF62–24.

[27] "Scientists and Engineers Admitted as Immigrants, by Occupation: 1962 to 1968," Statistical Abstracts of the U.S. (1970) 531.

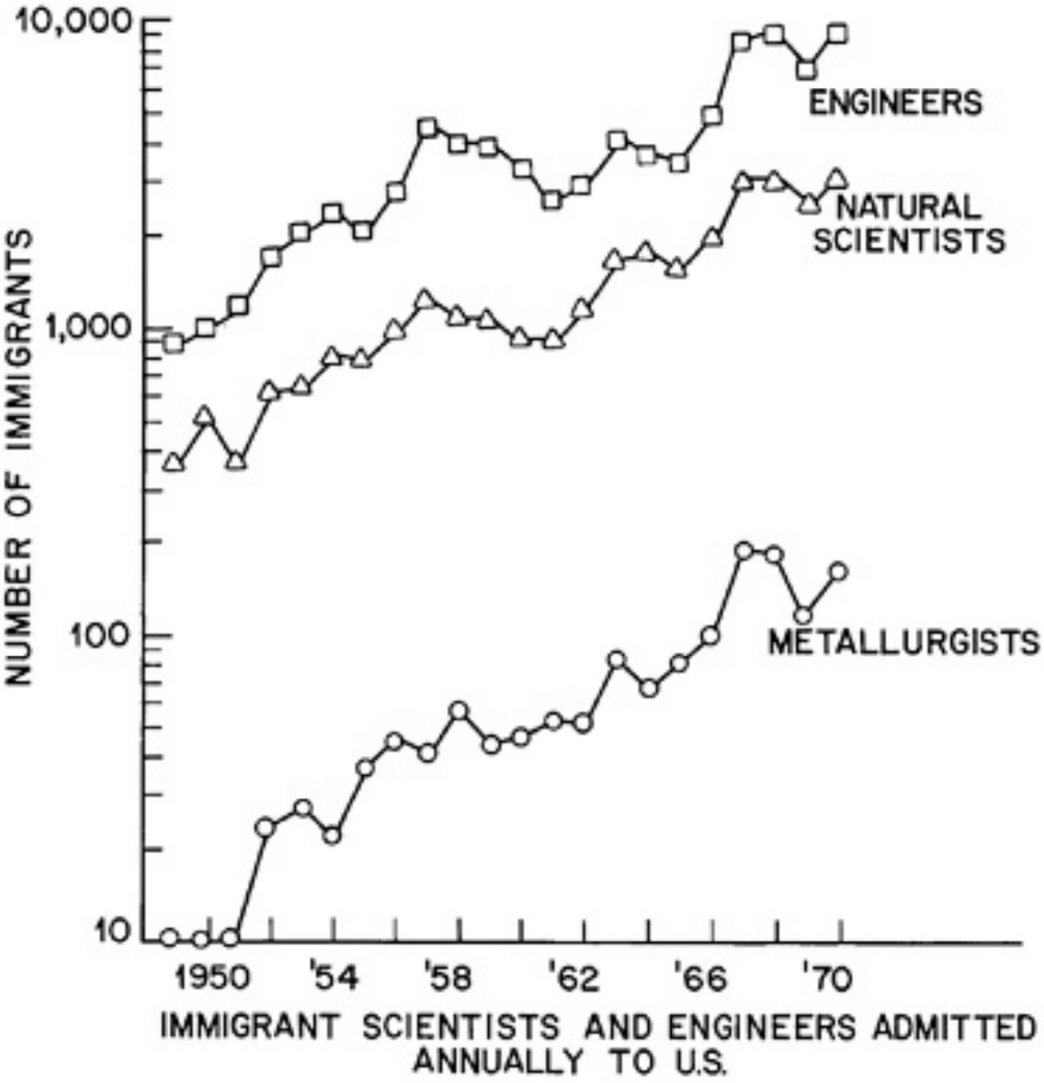
10,000
1,000
100
10
NUMBER OF IMMIGRANTS
ENGINEERS
NATURAL SCIENTISTS
METALLURGISTS
1950
'54
'58
'62
'66
'70
IMMIGRANT SCIENTISTS AND ENGINEERS ADMITTED ANNUALLY TO U.S.

FIG. 7.52

go abroad for “scientific purposes.” There are indications that some scientists and engineers are immigrating from the U.S. to other countries, but the number is not known.[28]

The slow-down in U.S. industrial activity in 1970 and 1971 led to unemployment among scientists and engineers. Accordingly, an attempt was made in the present study to determine whether and to what extent the professionals working in materials differed in their proportion of jobs lost. Data on unemployment among engineers for the months June-July 1971 were obtained in a survey conducted by the Engineers Joint Council at the request of the National Science Foundation. The questionnaire was sent to about 100,000 engineers constituting a 20-percent sample of a mailing list of major engineering professional societies. This list included about 40% of the engineers in the nation. About 65% of the engineers responded to the questionnaire. Since the survey included only a sample of the engineering population, the resulting numbers may not be taken as absolute values; however, the relationships between numbers may be considered significant. Moreover, the data apply to members of engineering societies and are not necessarily representative of all engineers.

The unemployment data for materials engineers in 1969 was 1.7% of Ph.D.’s and 2.2% for non-Ph.D.’s. In June 1970–71, it was found that 2.8%[29] of the professionals in metallurgy were unemployed and another 1.7%[30] had an employment problem, i.e., they were working part-time or in a job that did not require an engineering background. Of course, metallurgy is only one category of the field of materials engineering. This unemployment of 2.8% is slightly less than the 3% average for engineers in general. Unemployment rates for individual fields in engineering are shown in Table 7.54.

For scientists, the National Science Foundation reported that 2.6% were unemployed in the Spring of 1971[31]; the unemployment rate of all scientists under 30 years old was 5.3%, and the unemployment rate for all scientists with Ph.D.’s was 1.4%. No separate data for scientists in materials were available.

The future demand for materials scientists and engineers, in large part because of the limitations in the detailed statistics available for such manpower, has proved impossible to determine directly. However, studies have been made for science and engineering as a whole and, assuming the field maintains its relationship discussed earlier and follows these trends, the findings may provide some useful indicators.

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[28] T.P.Southwick, “Brain Drain’s Fewer Scientists Enter U.S., More Seek to Leave,” Science 169 (August 7, 1970) 565–566.

[29] “Unemployment Rate for Engineers, June-July 1971,” Science Resources Studies Highlights, National Science Foundation, September 23, 1971, NSF 71–33.

[30] “Employment and Career Opportunities,” ASM News (November 1971) 11–12.

[31] “Employment and Career Opportunities,” ASM News (October 1971) 11–12.

TABLE 7.54 Rates of Unemployed Engineers by Field of Specialization, 1971

Field of Specialization	Unemployed Rate (percent)
Engineering Specialization:	
Aerospace engineering	5.3
Chemical engineering	1.9
Civil engineering	1.2
Communications	2.9
Electrical engineering	2.2
Electronics engineering	5.3
Engineering, general	2.0
Environmental/sanitary engineering	1.6
Industrial engineering	2.8
Manufacturing engineering	4.5
Mechanical engineering	2.8
Metallurgical engineering	2.8
Petroleum engineering	0.7
Plant/facilities engineering	2.3
Product engineering	3.1
Systems engineering	4.1
Other engineering	2.1
Nonengineering specialization:	
Computer/mathematics	3.7
Management/business administration	3.0
Other nonengineering	4.5
No report	4.9

Source: National Science Foundation (Reference 29, page 7–240)

Brode[32] has argued that the potential supply for scientists and engineers is approximately a fixed percentage of the total population. The annual new supply will be approximately 3.8% of the number of persons reaching age 22, for this percentage seems to represent a ceiling on the number who are motivated and qualified to earn degrees in science and engineering. He concluded that there will be an annual surplus of scientists and engineers until 1986, and a deficit from 1986 to 2005 with the 1968–1986 surplus being about equal to the 1987–2005 deficit. Cartter[33] studied the doctor's degrees in the sciences through 1985 and the number of new faculty members required through 1990, and concluded that the demand for new doctors as faculty replacements will be much less than the supply. Thus, people holding new doctor's degrees will probably turn to the industrial job market in larger numbers during the 1970's than heretofore. In 1971, Terman[34] stated, "It is clear that the production of Ph.D.'s in science and engineering cannot continue to expand in the 1970's as it did in the 1960's. In fact, the great consumers of Ph.D.'s in the 1960's, namely academic institutions and defense and space activities, will require substantially fewer new Ph.D.'s during the 1970's. While industrially funded research will continue to grow at perhaps twice the rate of increase of the gross national product, this is not enough to take up the slack. Accordingly, if the new magnificent educational establishment that now exists in this country for producing highly trained scientists and engineers is not to wither away, new outlets must be found for its product. This means searching out new needs and hitherto neglected opportunities, and then developing the manpower markets thus defined." Wolfe and Kidd[35] examined the future market for Ph.D.'s and concluded that the rate of Ph.D. production must be reduced because the traditional markets for Ph.D.'s i.e., college and university teaching and research or R&D positions in industry and government, cannot absorb the Ph.D.'s of the 1970's. Many of these Ph.D.'s will have to find other types of positions. Wolfe and Kidd further suggest that the academic community and the government must develop a collective policy which will reduce the rate of production of Ph.D.'s in the future.

The NSF projections[36] for the supply and utilization of science and engineering doctorates in Engineering. Physical Sciences, and Mathematics are summarized in Table 7.55. It should be noted that these are projections and not predictions and should not be considered as valid for individual disciplines. The basic methodology employed by NSF in this study was that of statistically projecting past and current trends, including reasonable

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[32] W.R.Brode, "Manpower in Science and Engineering Based on a Saturation Model," Science 173 (July 16, 1971) 206–213.

[33] A.M.Cartter, "Scientific Manpower for 1970–1985," Science 172 (April 9, 1971) 132–140.

[34] F.E.Terman, "Supply of Scientific and Engineering Manpower: Surplus or Shortage," Science (July 30, 1971) 399–405.

[35] D.Wolfe and C.U.Kidd, "The Future Market for PhD's," Science 173 (August 27, 1971) 784–793.

[36] "1969 and 1980 Science and Engineering Doctorate Supply and Utilization," National Science Foundation, NSF 71–20, May 1971.

TABLE 7.55 Projected Supply and Utilization of Engineering, Physical Sciences, and Mathematics Doctorates in the U.S. in 1980

LEVEL OF SUPPLY/ UTILIZATION	ENGINEERING		PHYSICAL SCIENCES		MATHEMATICS	
SUPPLY						
High Supply	57600		84400		25200	
Low Supply	53700		80100		25200	
HIGH UTILIZATION						
Academic	16500	38.9	28700	32.6	18300	83.6
Nonacademic R&D	14600	34.4	39100	44.4	1100	5.0
Nonacademic other	11300	26.6	20300	23.0	2500	11.4
Total	42300	99.9%	88100	100.0%	21900	100.0%
LOW UTILIZATION						
Academic	16300	44.4	28000	37.0	18200	85.8
Nonacademic R&D	12500	34.0	33500	44.3	1000	4.7
Nonacademic other	7900	21.5	14100	18.7	2000	9.4
Total	36700	99.9%	75600	100.0%	21200	99.9%
MEDIAN SUPPLY	55600		82250		24350	
MEDIAN UTILIZATION	39550		81850		21550	
SURPLUS	16100	(40%)*	400	(0.5%)*	2800	(13%)*

* Surplus is shown as a percentage of median utilization.

variations, into the future. Probably, the more significant finding of this study is that there may develop a surplus of about 16,000 doctorates in Engineering in 1980. This means that, based on the projections, about 40% of the Engineering doctorates available in 1980 will have to find employment outside of the traditional academic and R&D areas. The supply and utilization of Physical Sciences doctorates appear to be in balance, and there appears to be a 13% surplus of Mathematics doctorates.

Professional Activities in the Materials Field

Joining a professional or technical society is a conscious act by an individual to declare his active participation in the field encompassed by that society. The motivation to do so differs from one person to the next; a survey by one of the materials societies found these objectives to be most important for individuals in such societies:

- To keep up with technology in the field of interest to an individual
- To associate with peers in the field
- To receive the publications of the society
- For business contacts
- To support the principles of the society
- For professional recognition
- To attend educational courses
- To obtain contacts for employment
- To join with others in the field as a unified voice in national affairs affecting the individual's profession

There are also other objectives, but it is clear from this survey that the main reason for joining a professional society is the person's desire to acquire, and remain current with, the body of knowledge which that society represents.

Inasmuch as the field of MSE is so broad and diverse, it is not surprising that there is no single materials science or materials engineering society; rather there are many technical societies in the field, often with quite different technical interests. The National Academy of Sciences listing of societies considered to have a significant materials activity is given in Table 7.56.

Again because of the field's diversity, persons who join one or another of the materials-related societies may not even be consciously relating to the materials field. Certainly members of societies like the American Ceramic Society, the American Institute of Mining and Metallurgical Engineers, the

TABLE 7.56 Listing of Materials and Materials-Related Professional and Technical Societies

1. American Association of Textile Chemists and Colorists
2. American Ceramic Society, Inc.
3. American Chemical Society
4. American Concrete Institute
5. American Electroplaters' Society, Inc.
6. American Foundrymen's Society
7. American Institute of Aeronautics and Astronautics
8. American Institute of Chemical Engineers
9. American Institute of Mining, Metallurgical and Petroleum Engineers, Inc.
10. American Iron and Steel Institute
11. American Nuclear Society, Inc.
12. American Oil Chemist's Society
13. American Petroleum Institute
14. American Physical Society
15. American Society for Metals
16. American Society for Quality Control, Inc.
17. American Society for Nondestructive Testing, Inc.
18. American Society for Testing and Materials
19. The American Society of Mechanical Engineers
20. American Society of Tool and Manufacturing Engineers (Now Society of Manufacturing Engineers)
21. American Vacuum Society
22. American Welding Society
23. Association of Iron and Steel Engineers

24. Federation of Societies for Paint Technology
25. The Fiber Society
26. Forest Products Research Society
27. The Institute of Electrical and Electronic Engineers, Inc.
28. Instrument Society of America
29. The Metallurgical Society of American Institute of Mining, Metallurgical, and Petroleum Engineers
30. National Association of Corrosion Engineers
31. Society for Experimental Stress Analysis
32. Society of Aerospace Material and Process Engineers
33. Society of Automotive Engineers Inc.
34. Society of Plastics Engineers
35. Electrochemical Society, Inc.
36. Electron Microscopy Society of America
37. Technical Association of the Pulp and Paper Industry

Society of Plastic Engineers, and the American Society for Metals are undoubtedly aware of their direct relation to the materials field because materials is the basic orientation of these societies. On the other hand, members of the American Society of Mechanical Engineers, the American Chemical Society, and the American Physical Society may be less aware of their connection to the materials field.

The questions thus arise: Should there be a single comprehensive society of materials science and engineering (or, for that matter, even several societies)? Or, a federation of materials-related societies? It is clear that a professional society must be responsive to the technical needs of the individual: i.e., his need for technical information in his field of activity through discussions and meetings with his peers, publications of the society, etc. Every professional has knowledge in a core set of technical principles such as chemistry, physics, mathematics, and has additional wider rings of knowledge which provide background for his more specific technical interests. The professional also needs a body of knowledge related to the major field of his occupation. Consequently, individuals tend to join those technical societies which come closest to their composite fields of interest, if this is possible. In addition, professionals often associate with divisions of a society having a more specific interest; for instance, the Polymers Division of the American Chemical Society. The fact that there are so many technical societies in the broad field of MSE suggests that the technical needs of materials professionals can be adequately met, but it requires several memberships.

However, for this very reason, the professional area of MSE faces various problems. Many societies with memberships less than about 10,000 are financially limited from providing a full range of services to their members, or even from offering their present services at the least cost. Combining certain staff functions of many societies such as publications, meeting arrangements, and even accounting, would reduce the fixed costs for each and thereby permit additional services. This kind of cooperation need not diminish the technical vigor and competitive character involved in the constituencies of different societies. Probably the greatest disadvantage of the separateness of professional societies in materials is that, with only a few exceptions, the individual societies are not large enough or strong enough to have a significant voice in public affairs and governmental actions which affect the individual professional or his technical field. An illustrative public policy issue is that the cost/benefit ratio in the disposal recycling of solid waste might be optimized by a broad materials approach which would lead to the installation of municipal waste-disposal systems to recover all materials of value for recycling, and to treat the remainder in the most efficient way for disposal. Another example of the value of a materials-system approach to national problems is furnished by the analysis in Chapter 5*about materials in transportation, which points out the problems and consequences involved in providing materials for automotive emission-control systems. A professional society representing the total materials field might better provide the public and the state and federal governments with technical guidance in such public issues.

There is no lack of such public policy issues. They include:

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* Chapter 5, Volume II, of this Series.

- Issues that concern science of engineering itself or a branch thereof: scientific manpower, education, and other matters that coincide closely with the interests of a given society.
- Issues of public welfare with a large technical component on which a society and its members can offer advice by virtue of their special knowledge.

In dealing with these issues, scientific and engineering societies have several options. They can develop and publish objective analyses of major problems. They can adopt or oppose a particular position in Congressional testimony, in dealings with federal agencies, by news releases, or in other ways. Societies or their members can form new groups specifically to cope with one or more special questions. All of these options are exercised from time to time by societies and special-purpose groups of scientists or engineers. The technical societies have tended to focus their efforts of this type at objective analyses of major problems in public policy that fall within their particular technical competence.

In this respect, scientific and engineering societies have found active encouragement from government on the grounds that failure of societies to involve themselves in the legislative process creates an imbalance in the flow of information to Congress. The ethical obligation of professionals to speak out on technical issues of public concern has recently been emphasized by the creation of a "Clearinghouse for Professional Responsibility." This body receives and investigates complaints of alleged unethical or wasteful practices of organizations and advises on possible courses of action when such practices are found. Technical societies could serve the public by judging whether or not this idea of a "Clearinghouse" has merit, and might consider undertaking a similar role themselves.

How can a professional society of materials science and engineering serve the varied technical needs of individuals in the field and at the same time speak out on broad national problems involving materials? A good possibility to achieve this lies in the recent formation of the Federation of Materials Societies. The formal examination of a Federation of Materials Societies started* at a meeting convened in March 1968 by the National Materials Advisory Board with the societies represented in the National Research Council. At least 36 societies have a significant degree of interest, and usually activity, in the general area of materials, although in many of these societies such interest is not dominant. Eighteen of the 36 societies believed to have a more identified interest with the materials field were invited to send representatives to an informal session for the planning of a conference on the subject in Washington on 14 August 1970. After subsequent discussions and planning sessions, ten of the societies agreed in 1971 to form a steering group to delve more deeply into organizational matters and to explore early opportunities for cooperative action.

The general reasons for establishing a Federation of Materials Societies formulated at these various meetings are as follows:

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* The idea itself arose much earlier in a Planning Committee Meeting of the American Society for Metals in 1963–64 under Professor Earl Parker.

- To assist in and to stimulate the establishment of a national materials information system and, by organized action, to solicit governmental aid as has been done by other federations or institutes.
- To provide an integrated mechanism to respond to governmental request for technical assistance, unified viewpoints, and so forth.
- To provide a means for compiling important data and statistics about the materials field and its constituents.
- To provide a deliberate and recognized forum for discussion of problems of mutual interest.
- To preserve the integrity of materials as an interdisciplinary field by providing the inputs needed, and to minimize fragmentation of existing groups into smaller specialized bodies; i.e., to serve as a unifying force for the materials community.
- To provide a means for enhancing the public image of materials as an entity and to provide an integrated channel of communication to the public and from the public.
- To promote improved quality and quantity of education, manpower, and facilities in the materials field.
- To provide a means for obtaining economies, collectively, in the publishing and distribution by the individual societies of their own journals, newspapers, and so forth, or alternatively, to facilitate joint ventures where desired.
- To provide a job clearinghouse and a mechanism for promoting transfer of techniques and personnel among materials scientists and engineers in various industries.
- To reduce unnecessary, unwanted, and costly duplication of efforts; for example, by providing a means for coordinating meetings and providing an integrated calendar of meetings.
- To provide means for analysis of government activities and legislation, through newsletters and other media.

These same discussions recognized that such a Federation:

- Is not a political lobby.
- Is not to be a new society.
- Is not to pre-empt any society in its own desired actions.
- Is not to deprive any society of its individuality, prerogatives,

autonomy, freedom of action, and so forth.

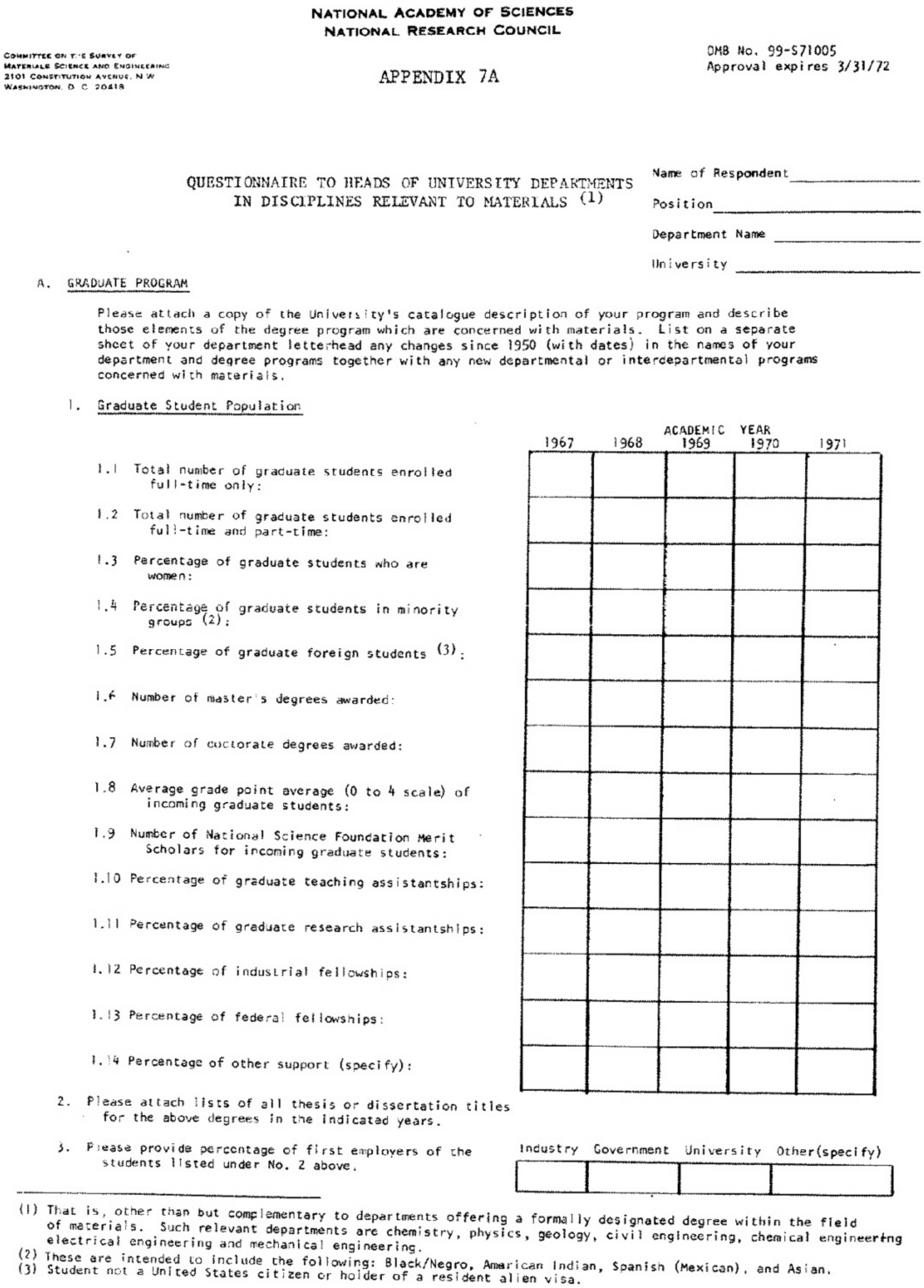
- Is not to use any form of coercion

At the present time, the Federation has the following 11 member societies (and several others in observer status):

American Ceramic Society
American Chemical Society
American Institute of Chemical Engineers
American Society for Metals
American Society of Non-Destructive Testing
Institute of Electrical and Electronic Engineers
National Association of Corrosion Engineers
Society of Manufacturing Engineers
Society of Plastics Engineers
The American Society of Mechanical Engineers
The Metallurgical Society of AIME

Among the activities in progress are: a survey of materials education activities in universities and technical societies, a life-cycle study of aluminum (as the beginning of a series), bibliographic reports on materials wastage by corrosion and wear, and an analysis of sources of technical information on materials. In addition, the Federation is initiating a newsletter Materials and Resources News.

APPENDICES



NATIONAL ACADEMY OF SCIENCES
NATIONAL RESEARCH COUNCIL

COMMITTEE ON THE SURVEY OF
MATERIALS SCIENCE AND ENGINEERING
2101 CONSTITUTION AVENUE, N.W.
WASHINGTON, D. C. 20418

APPENDIX 7A

OMB No. 99-S71005
Approval expires 3/31/72

QUESTIONNAIRE TO HEADS OF UNIVERSITY DEPARTMENTS IN DISCIPLINES RELEVANT TO MATERIALS (1)

Name of Respondent ______________

Position ______________

Department Name ______________

University ______________

A. GRADUATE PROGRAM

Please attach a copy of the University's catalogue description of your program and describe those elements of the degree program which are concerned with materials. List on a separate sheet of your department letterhead any changes since 1950 (with dates) in the names of your department and degree programs together with any new departmental or interdepartmental programs concerned with materials.

1. Graduate Student Population

	ACADEMIC YEAR				
	1967	1968	1969	1970	1971
1.1 Total number of graduate students enrolled full-time only:					
1.2 Total number of graduate students enrolled full-time and part-time:					
1.3 Percentage of graduate students who are women:					
1.4 Percentage of graduate students in minority groups (2):					
1.5 Percentage of graduate foreign students (3):					
1.6 Number of master's degrees awarded:					
1.7 Number of doctorate degrees awarded:					
1.8 Average grade point average (0 to 4 scale) of incoming graduate students:					
1.9 Number of National Science Foundation Merit Scholars for incoming graduate students:					
1.10 Percentage of graduate teaching assistantships:					
1.11 Percentage of graduate research assistantships:					
1.12 Percentage of industrial fellowships:					
1.13 Percentage of federal fellowships:					
1.14 Percentage of other support (specify):					

2. Please attach lists of all thesis or dissertation titles for the above degrees in the indicated years.

3. Please provide percentage of first employers of the students listed under No. 2 above.

Industry	Government	University	Other(specify)

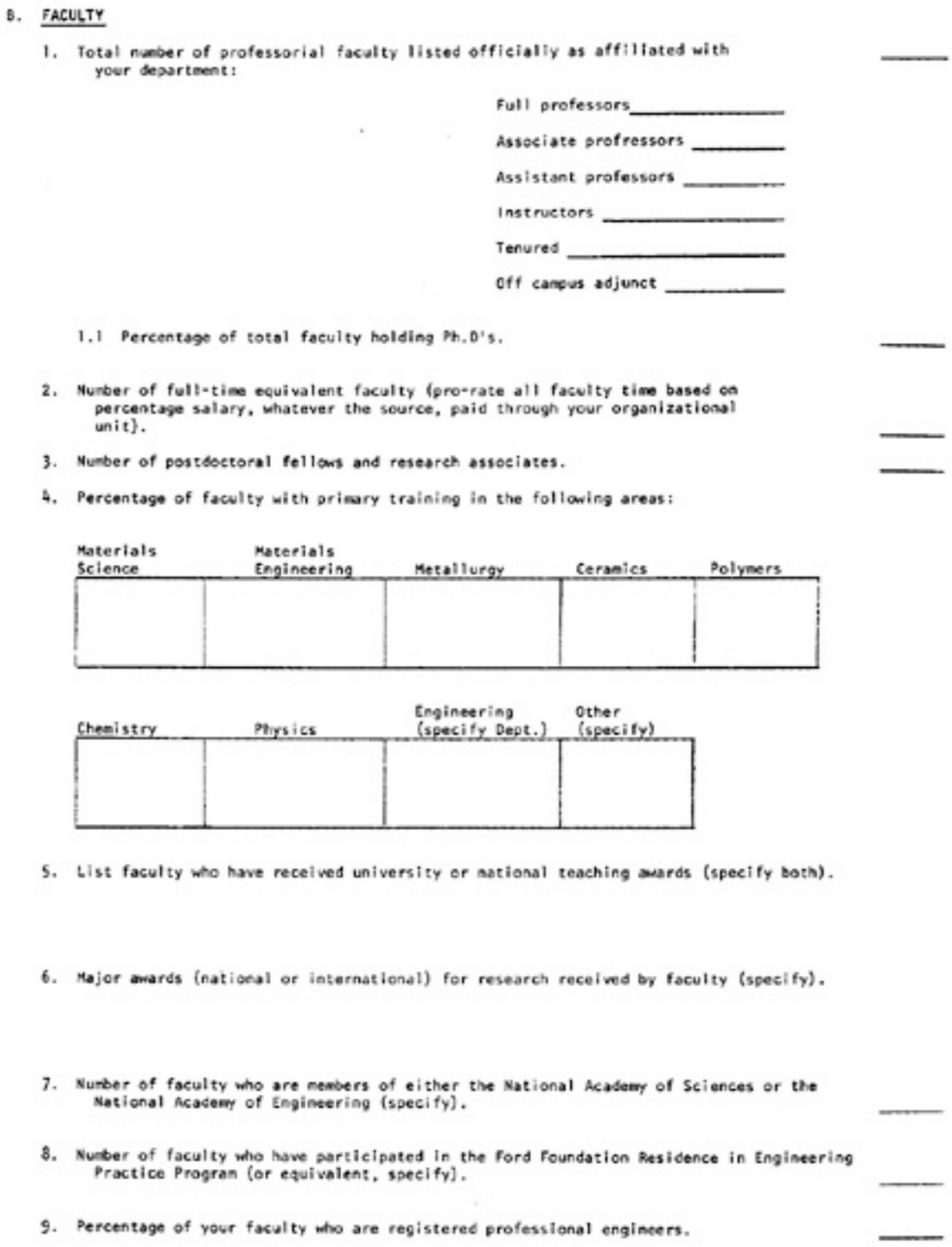
---

(1) That is, other than but complementary to departments offering a formally designated degree within the field of materials. Such relevant departments are chemistry, physics, geology, civil engineering, chemical engineering electrical engineering and mechanical engineering.

(2) These are intended to include the following: Black/Negro, American Indian, Spanish (Mexican), and Asian.

(3) Student not a United States citizen or holder of a resident alien visa.

Q2–2.



B. FACULTY

1. Total number of professorial faculty listed officially as affiliated with your department: ______

Full professors ______

Associate profressors ______

Assistant professors ______

Instructors ______

Tenured ______

Off campus adjunct ______

1.1 Percentage of total faculty holding Ph.D's. ______

2. Number of full-time equivalent faculty (pro-rate all faculty time based on percentage salary, whatever the source, paid through your organizational unit). ______

3. Number of postdoctoral fellows and research associates. ______

4. Percentage of faculty with primary training in the following areas:

Materials Science	Materials Engineering	Metallurgy	Ceramics	Polymers

Chemistry	Physics	Engineering (specify Dept.)	Other (specify)

5. List faculty who have received university or national teaching awards (specify both).

6. Major awards (national or international) for research received by faculty (specify).

7. Number of faculty who are members of either the National Academy of Sciences or the National Academy of Engineering (specify). ______

8. Number of faculty who have participated in the Ford Foundation Residence in Engineering Practice Program (or equivalent, specify). ______

9. Percentage of your faculty who are registered professional engineers. ______

Q2–3.

C. FRACTION OF DEPARTMENT ACTIVITIES DIRECTED TO MATERIALS

1. Please provide your own subjective estimate -- expressed as a single rounded percentage figure -- of the degree to which you and the faculty regard teaching and research in your department to be relevant to materials science and engineering. We are requesting this estimate at two levels of discrimination within the field as follows:

1.1 What percentage of your faculty student and research effort have been concerned with problems which are relevant to the scientific understanding of materials ________%

1.2 What percentage of your students would qualify, in your opinion, to be considered as materials scientists or materials engineers. This proportion could be estimated on the basis of the following parameters: ________%

(a) Extent to which courses offered and taken might especially qualify a student for research in the field of materials.

(b) Extent to which the thesis topic is concerned with materials.

(c) Extent to which the first job (where known) is in materials education or research.

NATIONAL ACADEMY OF SCIENCES

NATIONAL RESEARCH COUNCIL

QUESTIONNAIRE TO HEADS OF UNIVERSITY DEPARTMENTS OFFERING MATERIALS DEGREES(1)

COMMITTEE ON THE SURVEY OF
MATERIALS SCIENCE AND ENGINEERING
2101 CONSTITUTION AVENUE, N.W.
WASHINGTON, D.C. 20418
OMB No. 99–S71005
Approval expires 3/31/72

Name of Respondent _______________
Position __________________________
Department Name __________________
University _________________________

PART I. DATA ON FACULTY AND STUDENTS

(If data are unavailable in your University on any particular question, omit and go on to the next.)

A. UNDERGRADUATE PROGRAM

Please attach a copy of the University's catalogue description of the current undergraduate program for the materials department. List on a separate sheet of your department letterhead any changes since 1950 (with dates) in the names of your department, degree programs, and other new departmental or interdepartmental programs concerned specifically with materials.

1. Undergraduate Student Population

(a. For Materials Departments only; b. For all Engineering Departments)

		ACADEMIC YEAR				
		1967	1968	1969	1970	1971
1.1 Total number of juniors and seniors enrolled:	a.					
	b.					
1.2 Total bachelor's degrees awarded:	a.					
	b.					
1.3 Percentage of students who are women:	a.					
	b.					
1.4 Percentage of students in minority groups(2):	a.					
	b.					
1.5 Percentage of foreign students(3):	a.					
	b.					
1.6 Percentage of students going on to graduate work from:	a.					
	b.					

---

(1) That is, departments offering formally designated degree programs within the field of materials and listed as such among the curricula accredited by the Engineer's Council for Professional Development (ECPD), in the annual degree statistics prepared by the Engineering Manpower Commission or in the annual Directory of Metallurgy/Materials Schools.

(2) These are intended to include the following: Black/Negro, American Indian, Spanish (Mexican), and Asian.

(3) Student not a United States citizen or holder of a resident alien visa.

Q2.

B. GRADUATE PROGRAM

Please attach a copy of the University's catalogue description of the current graduate program for the materials department. List on a separate sheet of your department letterhead any changes since 1950 (with dates) in the names of your department and degree programs, together with any new departmental or interdepartmental programs concerned specifically with materials.

1. Graduate Student Population

(a. For Materials Departments only; b. For all Engineering Departments)

		ACADEMIC YEAR				
		1967	1968	1969	1970	1971
1.1 Total number of graduate students enrolled full-time only:	a.					
	b.					
1.2 Total number of graduate students enrolled full-time and part-time:	a.					
	b.					
1.3 Percentage of graduate students who are women:	a.					
	b.					
1.4 Percentage of graduate students in minority groups:	a.					
	b.					
1.5 Percentage of graduate foreign students:	a.					
	b.					
1.6 Number of master's degrees awarded:	a.					
	b.					
1.7 Number of doctorate degrees awarded:	a.					
	b.					
1.8 Average grade point average (0 to 4 scale) of incoming graduate students:	a.					
	b.					
1.9 Number of National Science Foundation Merit Scholars for incoming graduate students:	a.					
	b.					
1.10 Percentage of graduate teaching assistantships:	a.					
	b.					
1.11 Percentage of graduate research assistantships:	a.					
	b.					
1.12 Percentage of industrial fellowships:	a.					
	b.					
1.13 Percentage of federal fellowships:	a.					
	b.					
1.14 Percentage other support (specify):	a.					
	b.					

2. Please attach lists of all thesis or dissertation titles for the above degrees in the indicated years.

3. Please provide percentage of first employers of the students listed under No. 2 above.

Industry	Government	University	Other (specify)

Q3.

C. FACULTY

1. Total number of professorial faculty listed officially as affiliated with your department: ________

Full professors ________________
Associate professors ____________
Assistant professors ____________
Instructors ________________
Tenured ____________________
Off campus adjunct ____________

1.1 Percentage of total faculty holding Ph.D's ________

2. Number of full-time equivalent faculty (pro-rate all faculty time based on percentage salary, whatever the source, paid through your organizational unit). ________

3. Number of postdoctoral fellows and research associates. ________

4. Percentage of faculty with primary training in the following areas:

Materials Science	Materials Engineering	Metallurgy	Ceramics	Polymers

Chemistry	Physics	Engineering (specify Dept.)	Other (specify)

5. List faculty who have received university or national teaching awards (specify both).

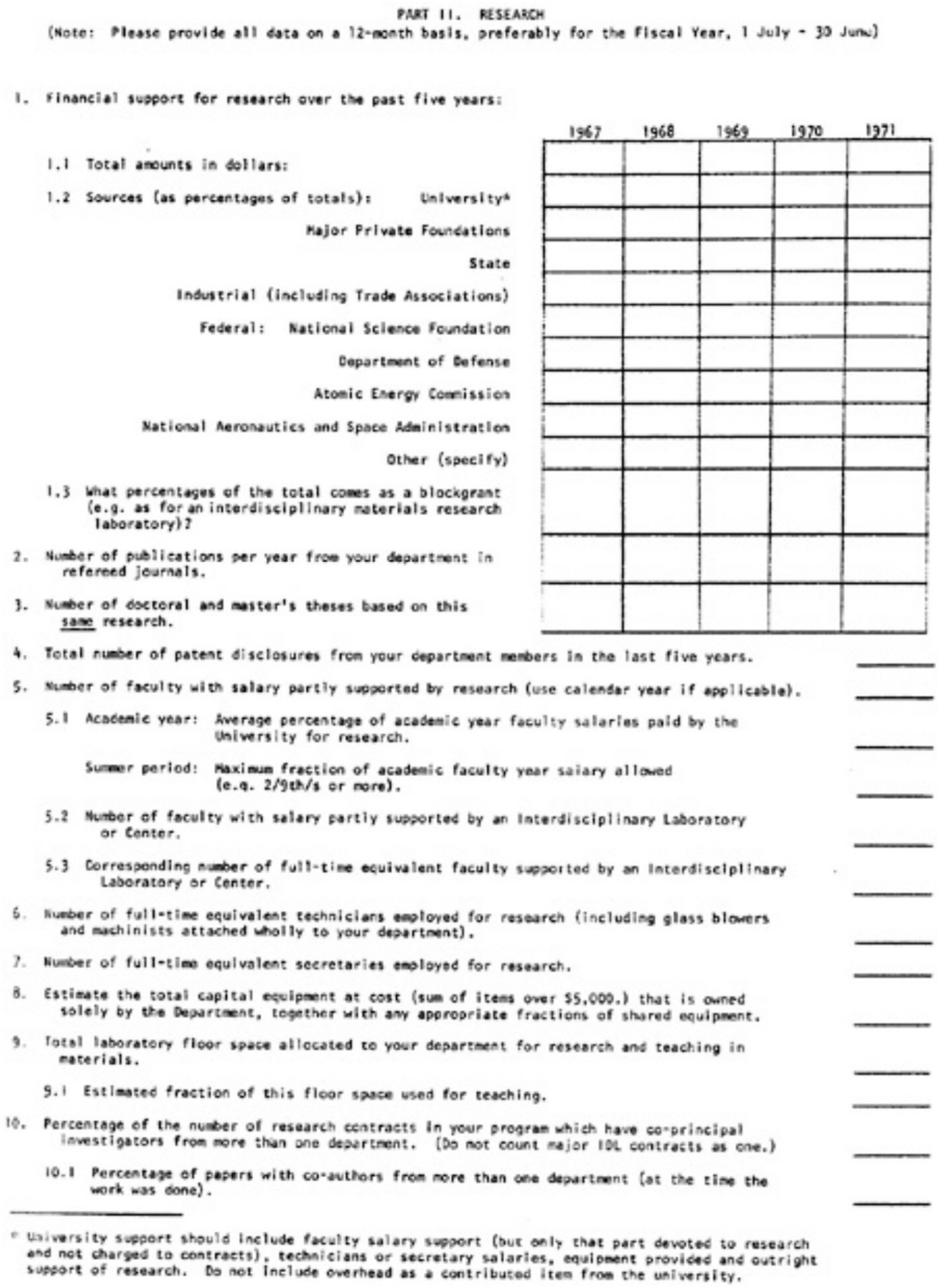
6. Major awards (national or international) for research received by faculty (specify).

7. Number of faculty who are members of either the National Academy of Sciences or the National Academy of Engineering (specify). ________

8. Number of faculty who have participated in the Ford Foundation Residence in Engineering Practice Program (or equivalent, specify). ________

9. Percentage of your faculty who are registered professional engineers. ________

Q4.



PART II. RESEARCH

(Note: Please provide all data on a 12-month basis, preferably for the Fiscal Year, 1 July - 30 June)

1. Financial support for research over the past five years:

	1967	1968	1969	1970	1971
1.1 Total amounts in dollars:					
1.2 Sources (as percentages of totals): University*					
Major Private Foundations					
State					
Industrial (including Trade Associations)					
Federal: National Science Foundation					
Department of Defense					
Atomic Energy Commission					
National Aeronautics and Space Administration					
Other (specify)					
1.3 What percentages of the total comes as a blockgrant (e.g. as for an interdisciplinary materials research laboratory)?					
2. Number of publications per year from your department in refereed journals.					
3. Number of doctoral and master's theses based on this <u>same</u> research.					

4. Total number of patent disclosures from your department members in the last five years. ________

5. Number of faculty with salary partly supported by research (use calendar year if applicable). ________

5.1 Academic year: Average percentage of academic year faculty salaries paid by the University for research. ________

Summer period: Maximum fraction of academic faculty year salary allowed (e.g. 2/9th/s or more). ________

5.2 Number of faculty with salary partly supported by an Interdisciplinary Laboratory or Center. ________

5.3 Corresponding number of full-time equivalent faculty supported by an Interdisciplinary Laboratory or Center. ________

6. Number of full-time equivalent technicians employed for research (including glass blowers and machinists attached wholly to your department). ________

7. Number of full-time equivalent secretaries employed for research. ________

8. Estimate the total capital equipment at cost (sum of items over $5,000.) that is owned solely by the Department, together with any appropriate fractions of shared equipment. ________

9. Total laboratory floor space allocated to your department for research and teaching in materials. ________

9.1 Estimated fraction of this floor space used for teaching. ________

10. Percentage of the number of research contracts in your program which have co-principal investigators from more than one department. (Do not count major IDL contracts as one.) ________

10.1 Percentage of papers with co-authors from more than one department (at the time the work was done). ________

---

* University support should include faculty salary support (but only that part devoted to research and not charged to contracts), technicians or secretary salaries, equipment provided and outright support of research. Do not include overhead as a contributed item from the university.

Q5.

II. Use the following scheme to present a bird's-eye view of the emphasis* of (a) the present, and (b) future research programs for your department.

(a) Where you are in 1971 based on dollar support:

	Electronic Materials	Metals	Ceramics	Polymers	Biomaterials	Other (specify)
More basic ↑						
More applied ↓						

(b) Where you will be in 1976 based on faculty interest:

	Electronic Materials	Metals	Ceramics	Polymers	Biomaterials	Other (specify)
More basic ↑						
More applied ↓						

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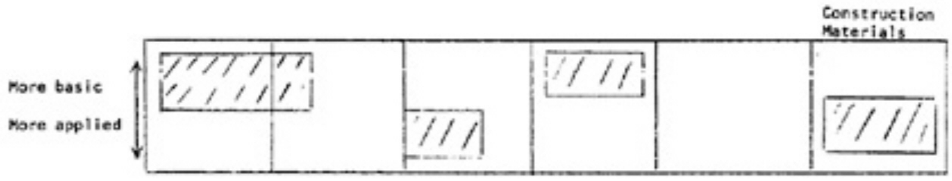
* An example might look like the following:



APPENDIX 7B

Some Examples of New Materials-Science Curricula

a. University No. 70. Name:	Solid State Science (Total Ph.D.'s so far: 120) Enrollment 50–75

This is an interdisciplinary program that cuts across departmental and collegiate lines. Faculty from various departments and with different backgrounds (e.g., chemistry, physics, fuel science, ceramics, electrical engineering, computer science, etc.) participate in the program. Master of Science and Doctor of Philosophy degrees are offered to students interested in pursuing an integrated and an interdisciplinary program of study encompassing both the necessary scientific fundamentals of chemistry, physics, and mathematics and their technological and engineering applications.

The program of courses taken by a student interested in the structure, properties, and behavior of solid materials must necessarily cut across two or more disciplines. The relevant subject matter has been grouped into four areas: (1) the structure of solids (crystal chemistry and structure determination); (2) theory related to the solid state (physics, chemistry, and mechanics); (3) properties of solids (optical, electrical, magnetic, mechanical, thermal and chemical); and (4) reactions of solids (phase equilibria, reaction mechanisms, reaction kinetics, and surface reactions). In addition there is the polymer science option which stresses appropriate aspects of organic polymers. The program of study is guided by a study panel consisting of members from the Solid State Science and related faculty.

The M.S. degree requires a total of 18 credits of course work (plus 12 in research), including substantial work in at least two of the above areas. The Ph.D. requires approximately 40–45 credits in course work plus research (no specific number of credits is required), distributed so that one discipline is encompassed in depth but with credits from all four areas. A thesis is required for both degrees.

b. University No. 75 Name:	Ph.D. in Polymer Science (Total Ph.D.'s so far:____) Enrollment_______

Advanced polymer programs leading to the doctorate and master's degrees are offered in both the Chemistry Department and the Materials Division. In addition, a polymer engineering option is presently being instituted in the Materials Engineering Curriculum leading to either a Master of Science or Master of Engineering degree. Undergraduate electives in polymers are frequently chosen by students in chemistry or chemical engineering curricula. Also, chemical engineering master's projects in polymers are available within the Professional School Program of the School of Engineering.

Formal courses in polymers are offered as follows:

Introduction to Polymer Physics
Introduction to Polymer Chemistry
Physical Chemistry of Solid Polymers
Physical Chemistry of Polymer Solutions
Organic Chemistry of High Polymers
Physical Properties of Polymers I and II
Polymerization Kinetics
Molecular Characterization of Polymers
Polymer Rheology
Polymer Science Laboratory
Viscoelasticity
Special Topics in Polymer Chemistry

The introductory courses are open to undergraduate and graduate students and are prerequisite for enrollment in the advanced courses. In addition to these courses, doctoral candidates in the polymer program frequently elect courses in the thermodynamics, instrumental analysis, physical chemistry, fluid mechanics, solid-state physics, x-ray diffraction and crystallography, rheological mechanics, applied mathematics, chemical reaction engineering, and fracture.

c. University No. 48 Name: Polymer Science and Engineering
(Total Ph.D.'s so far_______)
Enrollment__________

The program offers a Ph.D. degree with thesis and two master's degrees, with and without thesis. The degree without thesis involves 30 credits of course work. Normally, a baccalaureate degree in physics, chemistry, or engineering is required to enter directly the advanced degree program. Course scheduling is arranged to accommodate regular full-time graduate students as well as industrial employees who wish to matriculate in the evening. A series of four core courses are required for all M.S. candidates. They are recommended for all Ph.D. candidates, who will generally build upon the material presented in these courses in preparation for passing the Cumulative Examination requirement. The core courses are as follows:

General:	PSE	501 Introduction to Polymer Sci.	3 credits
PSE	502 Polymer Sci, Lab.	2	
Polymer Science:	PSE 793	Organic Polymerization Reactions	3
PSE 794	Physical Chem. of High Polymers	3	
Polymer Engineering:	PSE 795	Rheology	3
PSE 796	Polymer Processing	3	

The overall Ph.D. curriculum, not including thesis, might be comprised of the following course credits:

Core courses (17) + PSE and technical electives (12) + seminar (4) + research proposal (2) = 36. For example, <u>specific sample Ph.D. programs could be the</u>

following:

1. Student with Chemistry-Physics emphasis (assuming B.S. in Chemistry)

Core courses	17 credits
Topics in Physical Chemistry or Organic Synthesis	3
Chemical Thermodynamics	3
Mechanical Properties of Materials	3
Solid State	3
Advanced Engineering Math.	3
Microscopy and Morphology of Polymers	3
Seminar	4
Total	39

2. Student with Engineering Emphasis (assuming B.S. in Chemical Engineering)

Core courses	17 credits
Chemical Engineering Thermodynamics	3–6
Advanced Chemical Engineering Calculations	3–6
Transport Phenomena	3
Chemical Reactor Design	3
Electronics Instrumentation	4
Seminar	4
Total	36–42

d. University No. 73 Name: Solid State Sciences
(Total Ph.D.'s so far______)
Enrollment about 60

In the area of solid-state sciences, there are some 15 faculty about evenly distributed among four departments: Aerospace and Mechanical Sciences, Electrical Engineering, Chemistry, and Physics, and there are about 60 graduate students, All but three of the faculty are physicists and most of the graduate students are either physics or chemistry majors. There is a wide choice of graduate courses among those offered by the various departments which permits crossing of the usual departmental boundaries. For instance, one can take "Solid State Theory" in Physics, "Physical Chemistry" in Chemistry, "Lattice Defects" in Aerospace and Mechanical Sciences,and "Surface Physics of Semiconductors and Insulators" in the Electrical Engineering Department. The structure and organization of the general examinations (partly written and partly oral) in the A.M.S. Department for the students in the solid-state area is as follows: The students take a one-day (written) General Physics Examination in the Physics Department followed later by interviews with the faculty and a General Examination (oral) covering usually Mathematics, Thermodynamics, Electricity and Magnetism, Statistical Mechanics, Quantum Mechanics, and Solid-State Theory. Substitution of such fields as Advanced Physical Chemistry or Solid-State Electronics is encouraged. Faculty from various departments participate in this Examination. All students are required to start <u>independent research</u> early in the first semester in one of the areas of interest to the departmental faculty as indicated in the enclosed sheet. This choice does not affect the choice of the <u>thesis subject</u>.

e. University No. 97 Name:	Materials Science and Engineering (Total Ph.D.'s so far: 14; M.S.'s: 14) Enrollment about 15

The present program was adopted by the School of Engineering and Applied Science in 1966.

The prime objectives of the program are to provide a graduate-level education in the engineering aspects of structural materials to as broad a spectrum of undergraduates as possible and also to provide a framework for industrial participation in academic programs. The general philosophy has been to maintain as flexible an arrangement as possible on course work and degree requirements and also to provide research opportunities that will develop an interest in engineering problems associated with technologically important structural materials.

Students with an interest in materials are funneled into the program through the sponsoring departments. Program faculty members then determine the academic program that best fits the individual student. An essential feature is that the program is small enough so that each student is able to choose a course of study that is best suited to his interests and research needs.

We feel this program represents a successful interdisciplinary approach to materials science. There has been a free interchange of students in our courses in polymer science, applied mechanics, and metallurgy as well as interaction between industrial personnel and the students. A number of students have conducted part or all of their research activities in industry's laboratories, several being involved there now. The major hurdles to a Sc.D. in addition to course work are:

1. A preliminary examination taken during the first semester of residence which is based primarily on the student's undergraduate training. In principle, it is supposed to tell the faculty if there are any general areas of knowledge in which the student is especially weak.
2. A research proposal qualifying examination taken by the end of the fourth semester in residence. It is a written and oral presentation of the objectives and justification of the research program that the student wishes to carry out. The objective is to focus the attention of the student on his research goals and to determine his ability to do independent research.

Since this university and most other universities do not have undergraduate specialization in the materials field, it is assumed that most of our students come into the program with little specific knowledge of materials science and engineering. We feel it will take several years of scholarly work before they can gain a perspective of the field. For this reason, we emphasize study toward a Sc.D. degree.

APPENDIX 7C

History of the Development of Interdisciplinary Materials Research Centers

The establishment of this major organizational experiment had its roots in suggestions from various quarters. Prominent among the formative influences was a group of industrial-research leaders from the major materials-consuming industries (General Electric, Bell Telephone Labs., etc.) who urged the government to upgrade the universities' capabilities for conducting the very expensive and sophisticated materials research, as well as the associated graduate educational programs, which modern technology demanded. Meanwhile, within the government, the AEC's Metallurgy and Materials Branch Advisory Panel recommended in December, 1955, that the AEC's program of fundamental materials research be significantly expanded. In addition to other opinions, the Panel stated that the primary need was for additional laboratory and office space, particularly at universities. The Panel concluded that many universities had reached the limit of their facilities for training graduate students in the materials sciences and recommended that the AEC find ways of accelerating the construction of such research facilities. Early in 1956*, four universities submitted proposals for the formation of materials research institutes:

Massachusetts Institute of Technology
Pennsylvania State University
California Institute of Technology
University of Illinois

These proposals were considered but not funded because of such questions as federal involvement in education and whether it was appropriate for the federal government to construct buildings on university campuses.

The issue was revived during the summer of 1958 when AEC, NASA, DoD, and NSF representatives met to discuss what could be done to alleviate the shortage of scientific manpower and research capabilities in the universities. At its first meeting on March 24, 1959, the Federal Council on Science and Technology (FCST) created the Coordinating Committee on Materials Research and Development (CCMRD) to advise it on the nation's materials problems. The Committee was composed of representatives from each of the national agencies concerned with materials.

In its first report presented at the April 28, 1959 meeting of the Federal Council on Science and Technology, the Committee stated that it found one of the major limitations to the nation's materials research efforts to be

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* An interesting precursor to such laboratories already existed in the University of Chicago's Institute for the Study of Metals, where faculty members from different departments were supported in their research on metals in a coherent way.

a shortage of technical manpower and the needed laboratory space and equipment. The Committee recommended, among other things, approval in principle of the establishment of interdisciplinary laboratories for materials research to be built on university campuses as a means of correcting the situation. The FCST accepted the Committee's recommendations.

Subsequently the AEC, the DoD through its Advanced Research Projects Agency (ARPA), and somewhat later NASA, initiated their programs of block support for materials centers at several universities.

The concept of block funding, with some degree of assurance of continuity, was new in the early 1960's. It was believed this form of support would provide the following advantages:

a) By concentrating funds in a few carefully selected universities, it would be possible to develop centers of excellence. The money could be used locally to add faculty of high quality in different disciplines in accordance with well-developed long-range plans.
b) Facilities and services comparable with those found in the best industrial research laboratories could be established.
c) Interdisciplinary interactions would be encouraged.
d) It would be possible to respond more effectively to special needs. This flexibility was expected to prove most beneficial to new faculty members and to established faculty who might wish to change their research areas.

APPENDIX 7D

Details of University-Industry Coupling Experiments

Introduction

The research climate in 1972 was such that almost every avenue for increasing the efficiency of the total national R&D enterprise was given consideration. At the end of a rapid growth period, when increased activity cannot come from substantial increases in funding, it becomes clear that one of the most promising areas for increasing R&D output is by more effective coupling of the three research sectors—university/industry/government. Furthermore, the field of materials is an ideal case study for lessons from the past.

COSMAT has included as one of the criteria which are characteristic of the evolving field of MSE the purposive nature or mission-orientation of the field. Certainly this feature distinguishes significant materials research from most traditional disciplinary scientific activities on the country's campuses, and one must assess its importance in university materials work. If much coupling is not in evidence in this field, it may have an adverse effect on the general case.

As the issue of relevance and the general demand for greater accountability are raised, it behooves the academic community to examine the nature and effectiveness of its interfaces with society. In an applied field such as MSE, one might have expected that the interface would be particularly strong— at least relative to other areas. Especially where materials centers have been established, such an interface would appear even more likely since these interdisciplinary units on a campus are the obvious points of contact with the "problems" of society—those identified by government and industry. Yet, many would argue that it is not at all certain that university interaction with industry is either desirable or valuable as a general phenomenon across the campus. It is possible that such interaction could dominate academic processes and warp its purposes where it is carried too far and undue dependency established. Furthermore, since the university is, increasingly, one of the major performers of the nation's basic research, over-emphasis on applied research might cut off the well-spring of future science. On balance in 1972, university coupling to industry seems far below optimum levels considering societal problems as a whole. It is of considerable interest here to examine the status in MSE; to compare the new materials centers with more traditional departments; and to compare block-funded with nonblock-funded centers.

As to interaction among universities themselves, we have seen since the 1950's the emergence of a variety of consortial arrangements wherever "Big Science" has been involved. Nuclear facilities (Argonne, Brookhaven) and astronomical observatories are examples. Materials science is neither the "Big Science" of physics nor the little science of the $50,000 grant for, say, organic chemistry. It is in a very real sense a middle science of the $500,000 block grant.

Traditional University-Industry Coupling Patterns

Of the ways in which universities interact with industry, the most widely practiced is consulting for industry by the faculty. While this brings, in principle, ideas and concepts developed with university or public resources to the private sector, it does little to couple the total system. There are no data on this consulting activity. A survey by discipline and by university would be invaluable in this connection. However, it appears that the faculty of the materials departments do as much or somewhat more consulting than the average in engineering departments.

A second mode of interaction is the direct research contract to a university department or center. This is an obvious and quite generally available mode of interaction, since almost every university and almost every industry have the mechanisms to permit such coupling. Here again, there are no data on the national situation classified by disciplines, research topics, industries, etc.

A variant of this mode is the research grant from industry to university, or occasionally vice versa, where the government provides the funds so that one institution becomes the prime contractor and the other the subcontractor. This practice is widespread; the DoD and NASA have utilized it to a considerable extent.

Fellowships are excluded from this category since they involve only general support of university purposes, with no deliberate interaction of the research systems. Intermediate between fellowships and direct coupling is the family of arrangements which may go under the name “industrial affiliates,” where the university as a whole has established a special relationship to various companies. This involves much more than research and, in any case, the interaction relative to any one department or area remains diffuse.

Present University-Industry Coupling Attempts in the Materials Field

The traditional coupling modes noted above are all utilized in the materials field. However, there is no obvious evidence of any sudden changes in the pattern in the last two decades, caused by the emergence of MSE. It would be of interest to conduct a national study to obtain the data on the extent, nature, and value of coupling via these traditional modes.

However, since 1960, several novel experiments have been tried in the nation. Many of them are in the materials field and deserve careful attention for what they can teach us when such experiments are clearly binary arrangements (i.e. between university and industry), and also when ternary arrangements (where the government also enters the relationship, usually by providing the financial support) are involved.

Binary Coupling in the Materials Field: Only four or five formally established programs have been identified, although one or two others may have escaped our attention where a materials center or department is coupled to a group of industries on a continuing basis. This excludes the vast number of individual time-limited contracts.

The descriptive literature on the various binary arrangements discloses a high degree of similarity among the programs. If survival is a test of fitness, these coupling arrangements indicate rather unambiguously the features required for success, and serve as models for similar attempts. Their features are:

a) The coupling unit of the university must be a homogeneous and relatively small unit (i.e., not the whole university or college, etc.). It must have a degree of excellence in its specialization to offer something outstanding to industry.
b) The industrial sector must be represented by a limited number of participating companies—approximately a dozen which are:

i) In the technological areas where the university unit is strong.
ii) Geographically close—with a typical limit of 200–300 miles. (Extreme interest occasionally compensates for distance and vice versa.)

c) The university typically offers the following:

i) Continuing and relatively personal interaction with a group of faculty.
ii) Access to various highly specialized instrumentation,
iii) Much quicker access to research results from a very wide base of publicly supported research.
iv) A one- or two-day meeting once (or twice) a year for all the participants.
v) Special facilities for personnel exchange. University faculty to lecture in industry, or industrial personnel to spend a few days to a few months at the university.
vi) Special notification of items or events of exceptional interest in the university.

d) What the industrial participants provide are:

i) Advice and insight into the problems of highest relevance to a particular industrial sector. This is a very important reason for a coupling program—the relevance input into the university.
ii) A modest "membership fee," usually of the order of a few thousand dollars (occasionally this is part of a larger research contract from the company). This sum gives the university unit the flexibility to nucleate the best idea-programs quickly; to help supplement a government grant for equipment; or to help a student starting or finishing his research on an odd cycle. The universal desire is to have

a small fund of money which may be used more flexibly than ordinary grants permit.

iii) Access to specialized and/or large equipment, and skills.
iv) Lecturers at university, and opportunity for faculty and students to work in industry.

Ternary Coupling Arrangements: Our cursory survey has identified only half a dozen examples of this model.

These arrangements are quite different from the binary category since they involve the actual research towards a defined objective, and support in the hundreds of thousands of dollars per year. The ARPA approach was aimed very specifically at advancing selected areas of technology, and was also an attempt to accelerate the transfer along the science ` engineering axis. According to R.L.Sproull[37]: “The ‘coupling’ in this context is no longer the joining of two institutions together, although many people seem to still think of the coupling in this program as the joining of an educational institution to an industrial laboratory. The coupling is simply one of the appropriate techniques, perhaps the most important one, that is available to a laboratory that has a responsibility for developing a field of technology. Certainly invention is also needed; we are not so naive as to believe that all of engineering development arises from science. Furthermore, as I have mentioned before, the coupling includes a great deal of joining of science developed elsewhere in the world and science developed right inside the industrial laboratory to the field of technology, as well as coupling of the science developed in the university or technical institute arm of the program.”

And this transfer, moreover, was also expected to happen within the university. Thus:

“As mentioned, in the original proposal the university components were to be science departments. With the broader view of the ‘coupling’ explained above, it became clear that the parts of the universities that could be most helpful would eventually be engineering departments. This is not to say that at the beginning an institution with a strong science department and a growing engineering department might not qualify. It is only to say that in the long run there should be a strong interaction between the engineering departments of the university and the industrial laboratory.”

Regrettably, no report has been prepared on the ARPA experiment. Of the three programs, the Washington University with the Monsanto Company is still funded and has resulted in the setting-up of an interdisciplinary focused-research laboratory and a corresponding degree program concentrating on composite materials. The University reports on its own program in the following terms:

“Prior to September 1965, activities in materials science and engineering at Washington University were limited to an informal program in Metallurgical Engineering. Part of the objective of the Monsanto/Washington University ONR/ARPA Association has been to provide a graduate-level education in the engineering aspects of structural materials to as broad a spectrum of undergraduates as possible and also to provide a framework for industrial participation in academic programs. The general philosophy has been to maintain as

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[37] R.L.Sproull, “ARPA ‘Coupling’ Program,” Internal Memo (May 1965).

flexible an arrangement as possible on course work and degree requirements and also to provide research opportunities that will develop an interest in engineering problems associated with technologically important structural materials.

"We feel this program represents a successful interdisciplinary approach to materials science. There has been a free interchange of students in our courses in polymer science, applied mechanics, and metallurgy as well as interaction between Monsanto personnel and the students. A number of students have conducted part or all of their research activities in the Monsanto Laboratories, several being involved there now."

The principal results are:

"That the Monsanto/Washington University Association program sponsored by the ONR/ARPA contract has been the primary stimulant for a Materials Science and Engineering Program at the University.

"That industry-university cooperation in a specific research area has led to a meaningful experience for a graduate student with the direct consequences being a better appreciation of the relevance of his research to the technological community, an acceleration of his research program, and a more stimulating environment in which to work.

"That we have developed a faculty and a mode of operation which hopefully will permit us to broaden our scope and sustain a well-balanced program of graduate study in structural materials."

Two major NSF models are still quite new: The Processing Research Institute at Carnegie-Mellon University states its objectives as follows:

"This institute will work closely with the basic industries of the country in order to establish a problem-oriented rather than discipline-oriented approach to engineering education. Three departments at CMU are involved in this activity—chemical, mechanical and materials engineering. The program will involve new subjects, new degree requirements and a greater emphasis on project work than in present programs. An effort will be made to involve students who have had at least one year of industrial experience in the program.

"The activities of PRI will have two major thrusts—one directed toward the generation of new knowledge and techniques for industry and one directed toward a new type of engineering education."

The Ultrahard Materials Program started in June, 1971 in the Engineering Division of NSF involves Case Western Reserve, Carnegie-Mellon University, Denver, University of Florida, M.I.T., Oregon Graduate Center, and Penn State University, The research at these institutions forms an approach to the basic and applied science level of problems relevant to the cutting and grinding industries. Presentation of the problems by, and feedback of results to, a group of industries are achieved in a semiannual meeting where highly specific reporting and critique take place. This model constitutes a highly generalizable university version of a government contract to a prime contractor and its subcontractors for a major item. Where there is no prime contractor, some degree of leadership must be created by one or other of the major participants in turn.

Other Inter-Institutional Models: Unique among industry-university coupling arrangements is the Materials Advisory Panel of the Governor's Science Advisory Committee of the Commonwealth of Pennsylvania. This Panel, in the tenth year of its existence, is a consortium of leaders of six major

Universities (Carnegie-Mellon, Drexel, Lehigh, Pittsburgh, Pennsylvania, and Penn State) and approximately ten major corporations. The Panel has been responsible for technology transfer in the materials field via federal and state programs utilizing conferences, workshops, TV, and movies, aimed principally at small and moderate-size companies. The programs have included one for industry research personnel internships at the universities' materials centers. The Panel has developed, encouraged, and participated in reviewing the intrastate coupled contracts between industry and universities which have been funded by the Pennsylvania Science and Engineering Foundation (PSEF) for many years. This program averaging a few contracts in the materials field every year, with a value aggregating to perhaps $200,000/year, is probably the most extensive experiment in coupled materials research in the nation. A preliminary analysis by the PSEF administrators of successful models delineated the following features as most conducive to success:

a) Demonstrated scientific experience, capability, and competence, plus a novel approach or idea.
b) Demonstrated previous performance of university sector in industry-related work (either consulting or research contracts).
c) Proximity of ease of communication among units involved.
d) Manpower from industry working in university (at least part-time).
e) Strong university management (since performance is evaluated by atypical criteria).

A quite different type of "coupling" may be the absorption by industry of some university functions. The General Motors Institute is an example of this where the corporation provides an education integrated with employment in its normal production processes. More typical of the usual teaching arrangements are the myriad in-house courses given by most major corporations. As yet there are only isolated examples (among them, those noted above) of universities gearing up for courses in MSE to be given within a single industry. The total volume of such continuing education is large and increasing, but the role of the university so far appears to be minor. An excellent opportunity for a new form of coupling exists here.