Basic Research in Materials

Academic research must become oriented toward possible limitations in materials resources and supply.

Robert A. Huggins

The concern about materials limitations, since World War II, has been interpreted as limitations on the capabilities of engineering structures and devices due to the properties of the materials from which they are constructed, particularly in uses demanding high performance. However, attention is more and more being directed in quite different directions, those in which technology is, or might be, limited by the availability of materials.

The implications of a change in emphasis toward possible limitations in materials resources and supply due to shortage and price are substantial. These limitations have special importance with regard to activities that have large momentum and change rather slowly, such as those characteristic of both the research and educational functions of the university.

This new set of interests presents a major challenge to the institutions whose role it is to provide the fundamental and longer range underpinning to technology. I believe that it is fair to say that the nation's academic institutions are ill-prepared for such a major change in direction, for they have attempted to optimize their activities to meet a quite different set of needs.

In this article I discuss some aspects of the nation's basic research activity and the realities of current "materials" concerns in academia, in order to provide some insight into this problem.

The New Needs

As attention is shifted toward questions of materials resources, it should be recognized that there are two rather different concerns. One has to do with potential shortages or price pressure in the relatively near term, and arises from the nation's recognized vulnerability to the curtailment of supplies, price escalation, or both, in several key industrial raw materials; it results primarily from our dependence upon imports of these commodities from relatively few suppliers.

Potential problems of this sort, which might arise within the next decade, have both technological and political components. Because of the latter, it is difficult to predict the need for, or the type of, specific remedies. It may also be too late for research and development that has not yet been done to have any appreciable effect.

The other major concern involves the ultimate limits of economically feasible resources, regardless of the time scale. One might reasonably expect that research and development could produce positive results in this context, either by working toward objectives which might increase the effective supply of specific materials resources, or by developing changes in technology that might reduce the demand for their utilization. In the latter case, there are only three choices. One can make more efficient use of materials, one can substitute other materials to perform the same functions, or one can lower the technological level of expectation, or standard of living. It is not simple to foresee the role that longer range, or basic, research, much of which is performed in the nation's universities, can play in these arenas without massive changes in both attitudes and activities.

The rapidly increasing interest in questions of materials resources is the second major new wind to blow across the research and development scene in the last few years. The first, of course, was the recognition of the importance of various similar energy-related questions. Energy resource problems have become apparent, and a number of steps have been taken to engage the nation's research and development apparatus to deal with them.

As we move into a future in which materials resources may also be severely limited, it is reasonable to expect the nation's basic research community to make a useful contribution. There are a number of important questions, however, about what that contribution might be and how it might be accomplished.

Fundamental Role of Universities

A major role of universities in our society is to provide advanced education to the part of the population that is expected to provide future leadership. An important aspect of this educational process involves the propagation of concepts and techniques with which constructive action can be undertaken. Part of the university function also involves development of these tools and their application to society's needs through research.

The current shift of interest into energy-related science and engineering on the university campuses, while difficult in some areas and impossible in others, is not nearly so traumatic as the potential consequences of a strong shift in emphasis to resource-related activities. The primary reason for this is that there are various energy-related scientific and technological areas that seem to fit reasonably well into what much of the academic research community thinks is of interest and can perform with competence. On the other hand, today's typical academic view is that the technical aspects of questions of materials resources primarily involve existing, if not antiquated, technologies, which are not research-oriented, and which have had less and less contact in recent years with universities. In short, these are not problem areas in which the basic research community has had a role in the recent past, and one is not apparent in the future.

However, it is easy to think that today's way of life is the expected normal and proper one and that any deviation would be inappropriate for a vast number of reasons. But man's memory tends to be surprisingly short, and fundamental changes can occur even in very old institutions in a relatively short time. For example, consider the immense changes that have occurred in the relationship between the nation's universities and the federal government within the last several decades. Except for agriculture (for example, experiment stations) and military training (ROTC), the universities were quite independent of the federal government in this country until World War II.

During and immediately afterward, the important influence of new technology (for example, radar, sonar, rocketry, and nuclear energy) became evident, and the importance of long-range basic research in

The author is the director of the Center for Materials Research, Stanford University, Stanford, California 94305.

providing the nutrient from which such technological developments can grow was recognized. Long-range federal research support in universities was initiated under the auspices of the Office of Naval Research, and the National Science Foundation was later established with that as one of its primary purposes.

In recognition of the fact that educated people constitute an important part of the technological capital of the nation, the federal research support apparatus was operated in such a manner as to optimize the output of trained scientists and engineers as well as to perform research. This has led to the present situation, in which the graduate programs at the nation's major academic institutions are highly dependent on federal research funds. In fact, such funds support a large number of graduate students in the universities, and changes in patterns of federal funding have an immense influence on both graduate education and university-based research. Such a fundamental shift in the relation between the government and the university was not foreseen even as recently as 2 decades ago; thus we should be somewhat hesitant about extrapolating far into the future.

Current Academic Paradigms

An interesting and thought-provoking analysis of the course of science was presented by Kuhn in *The Structure of Scientific Revolutions* (*1*). One of his major themes is the role played by paradigms, which he describes as accepted models, concepts, patterns of thought, and techniques that define coherent traditions in specific research areas. Successful practitioners in what he calls "normal science" share these paradigms and are committed to a generally accepted set of rules and standards that define both a common body of belief and also a way of looking at and dealing with their particular technical areas. Kuhn observed that an existing paradigm supplies criteria for choosing problems; to a large extent, only work which satisfies these criteria will be recognized by the community as scientifically sophisticated and worthy of being undertaken. Activities in other areas are typically rejected as being metaphysical, the concern of another discipline, or too full of problems to be worth time and attention. Thus, at any given time in a specific field, there are a finite number of problem areas that are considered worthy of attack and sufficiently tractable that they merit attention.

It follows that prestige is allotted in accordance with the current version of the paradigms in a given field. Fashions change, and what is considered respectable and valuable shifts with time. One can perceive the validity of these observations by noting the trends in the selection of Nobel laureates.

Kuhn also pointed out that a scientific community can be constrained and insulated from important problems that are not susceptible to the conceptual and instrumental tools of its current paradigms. In some cases, this can result in an increasingly narrow approach in which finer and finer detail is articulated within a limited range of activities; the discipline feeds more and more upon itself and its self-generated problems with decreasing relevance to the external community.

According to this model, changes to new paradigms occur in science through revolutionary, rather than evolutionary, processes. They arise from the recognition of anomalies in which the existing and generally accepted paradigm fails. A new paradigm emerges; there is a period of conflict between the new revolutionary approach and the previously established articles of faith; and one approach finally becomes dominant.

If one applies this thinking to academic institutions, it becomes apparent that the paradigms that have developed during the last several decades have been such that basic science (as compared to applied work) has carried more prestige and has had a greater payoff in most academic fields. This has been true not only in the scientific disciplines, but also in those nominally called "engineering."

This point of view has been strongly reinforced by federal research support mechanisms, in which peer judgment has played a substantial role. Persons making the decisions, both in and outside of the government, have generally been associated with the scientific disciplines themselves, and they quite rationally aim to see that federal funds are utilized to support research work of the highest quality and relevance—in terms, of course, of the existing paradigms.

It is also not surprising that this internal feedback mechanism results in a concentration of academic research on problems that can be described as opportunity-driven rather than need-driven. In many cases, problems are selected and solved because their solution is feasible or interesting from the standpoint of the discipline rather than because of the external pressure of an applicational need. It is no wonder that turmoil resulted from the sudden imposition of the concept of need-based relevance a few years ago.

What happens in universities has an especially important influence on the establishment and reinforcement of paradigms, for the university's training activities are highly biased by the competition and selectivity resulting from the federal research support mechanism, not just in terms of the specific research undertaken on the campus, but also with respect to attitudes, value systems, and expectations. Neophytes are indoctrinated in their professional paradigms during this stage of their careers.

"Materials" Within the Nation's Universities

The discipline of materials science and engineering has been evolving on university campuses for the last 15 years or so. This process has occurred by the agglomeration of a number of activities previously existing within other more traditional disciplines. After much confusion and contention, it is now evident that materials science and engineering is emerging as a coherent technical field and that a new paradigm is developing.

A major stimulus to this field arose in the late 1950's, when it became recognized that problems involving materials technology constituted serious impediments to progress in a number of areas of great national importance, particularly in atomic energy and technologies related to defense. Special attention was also called to matters related to space and defense because of the appearance of Sputnik in late 1957. Because the properties of materials often limited the performance of devices and systems, the development of sophisticated new devices and systems was dependent on progress in the materials area.

After much deliberation—involving the President's Science Advisory Committee, the Federal Council for Science and Technology, and the Coordinating Committee for Materials Research and Development—a long-range interagency program was initiated to provide a special stimulus to the field of materials science. The people taking part in those early studies recognized that the primary difficulty was not merely that more effort in materials technology was needed, but instead, that much of what was being undertaken was lacking in sophistication and effectiveness because it was not sufficiently grounded in adequate scientific understanding of the physical phenomena involved. They also recognized that an important limitation was that there were too few people available with appropriate scientific training.

Three federal agencies, the National Aeronautics and Space Administration (NASA), the Atomic Energy Commission (AEC), and the Department of Defense, agreed to share the responsibility for giving materials science a push because of its relevance to their interests. One result was a large infusion of funds (about $8 million) to upgrade capital equipment in 79 universities active in materials research. The second, and perhaps more important result, was the initiation of 17 major long-term university programs of a multidisciplinary type. After receiving 76 university proposals, the Advanced Research Projects Administration, acting for the Defense Department, initiated 12 of these programs; the other 5 programs were supported by NASA and the AEC. In each case the purpose was to improve both the quality and quantity of the materials science.

Detailed information on these programs is available (*2–4*). It should be pointed out here that the programs and their antecedents have had an important influence in setting the tone of materials research on the university campus.

One especially important development is the recognition of materials science as a generic field. It is now widely realized that significant similarities exist between many classes of materials (for example, metals, ceramics, and polymers) with respect to structure, phenomena, properties, and processes. Emphasis is increasingly being placed on similarities between these classes of materials and the generalizations that can be made about them, rather than their being treated separately.

In addition, the understanding of the nature and behavior of materials has become more sophisticated. This has resulted in large measure from the development of the interdisciplinary aspects of this field. Concepts, tools, and techniques developed in one academic discipline are now being applied in areas traditionally assumed to be the domain of another.

As a result of this program and other influences, the emphasis has been on materials science rather than on resource questions. The current academic interpretation of materials science centers on the relation between the structure and properties of materials as a basis for their design, preparation, and utilization. A recent report (*4*), prepared under the auspices of the National Academy of Sciences, defined materials science and engineering as being "concerned with the generation and application of knowledge relating the composition, structure, and processing of materials to their properties and uses." Although this definition is broad, the important point is that it focuses on properties rather than upon questions of availability, which are the concern of many of the other papers in this issue of *Science*.

The obvious conclusion is that "materials" means something quite different to its current practitioners than it does in the context of this new concern about resource questions. If the nation is going to expect this part of its scientific and technological apparatus to perform a different type of service in the future from that toward which it is currently focused, important changes in course must be undertaken.

Unfortunately, today's typical academic view is that the technical aspects of materials resource questions lie in the domain of fields that, to much of the university community, are considered antiquated, technological (rather than scientific), not oriented toward research, and not really very interesting. To put it bluntly, many people would probably contend that materials science has charged ahead in more science-intensive (high-technology) areas, leaving such experience-intensive (low technology) activities behind in the dust. The record shows that the preparative side of materials science and engineering has long been underfed by federal funds, underpopulated by students, and undersupported by academic administrations.

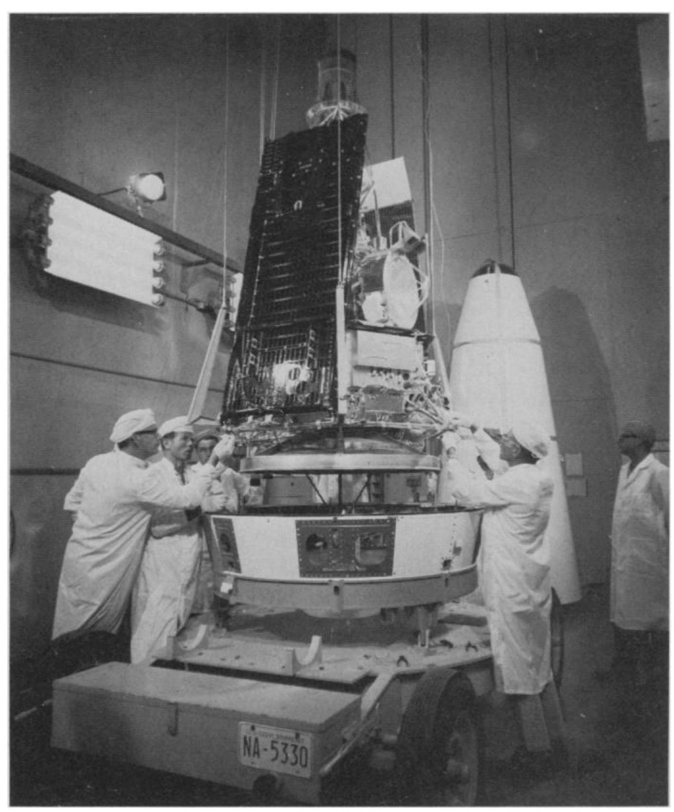
Comments on Future Roles

As has been pointed out above, much of the academic research effort in the past several decades has been oriented toward increasing the depth and sophistication of scientific disciplines themselves. This has also resulted in the development of many new technologies and has been in tune with two very important external influences, the relative availability of federal research funding and the pressure of the job market, which has been heavily biased in favor of the developing (rather than aging) technologies.

During the past 15 years or so, materials science has become a coherent and visible field, and the people in several of the more traditional disciplines are recognizing it as a common base. More recently the major question has shifted from whether materials science will become a stable field, to where it will go in the future.

Much of the growth in activities related to industrial materials has also been in the more sophisticated or science-intensive areas, rather than in those that are more experience-intensive. Industrial growth and the job opportunities for academia's product tend to be where the rate of change is high.

If materials resource concerns do indeed become important, the problem of the reorientation of the basic research community will not be easily solved, because of the momentum in other directions that has been established over the last several decades. However, this problem is not unique to basic research or to universities. It was argued by Hollomon and Harger (*5*) that the concentration of federal research and development funding on matters related to defense, space, and atomic energy has resulted in a reduction in both the magnitude and the quality of industrial research and



With the appearance of Sputnik in the late 1950's, special attention was called to materials related to space. The development of sophisticated new devices and systems was dependent on progress in the materials area. [National Aeronautics and Space Administration] development related to other (civilian) needs in the economy. They contended that in addition to the bias exerted directly by selective expenditures of funds in certain areas, there was economic competition for available trained personnel, which tended to concentrate most of the effective scientific and engineering personnel in those fields receiving greatest federal support. They, among others, have pointed out the serious decline in our relative competitive position in an area in which this country used to be paramount—general industrial productivity.

Contrary to the conventional wisdom, it is now apparent that, in many important cases, the major reason for the encroachment of Japanese and European technology upon traditional American markets is not directly related to hourly labor costs. Instead, it is often due to increased sophistication and productivity in industrial production technology. Governmental policies and practices can have a large influence upon the disposition of available resources, including the technical labor force (*6*).

With regard to basic research and the university role, there are things that can be done to begin to utilize this set of national assets to alleviate some long-term materials resource constraints. It will be important, however, to focus on the optimum use of existing strengths, rather than to precipitously dismantle the apparatus that has been established for the successful pursuit of other goals. We should carefully think through the types of activities that can fit well into effective patterns of university, as well as industrial, action, rather than rushing off to make basic changes in our institutions.

Development of useful alternatives over the long run is much more than simple substitution among existing resources. In order to have more than a transient impact, we need to understand where, and more importantly, why, important materials are currently used. Knowledge of their functions (in fundamental terms of the structure and properties of the materials employed) in devices and of the various phenomena that control them will be important.

These questions are, of course, near the heart of the current paradigm in materials science; if this information were elucidated, sophisticated materials engineering might develop alternatives with the same property-related function as the commodity whose availability is under question.

It is imperative that we encourage increased attention to such matters by the nation's universities in such a way as to build upon existing strengths. Part of the problem will certainly be to interest and excite a community that has been oriented in a different direction and marching to a different drummer.

References and Notes

1. T. S. Kuhn, *The Structure of Scientific Revolutions* (Univ. of Chicago Press, Chicago, ed. 2, 1970).
2. C. F. Yost and E. C. Vicars, *J. Met.* **14**, 666 (1962).
3. R. A. Huggins, in *Proceedings of the Conference on the National Materials Policy* (Government Printing Office, Washington, D.C., 1970), p. 229.
4. Committee on the Survey of Materials Science and Engineering (COSMAT), *Materials and Man's Needs* (National Academy of Sciences, Washington, D.C., 1974).
5. J. H. Hollomon and A. E. Harger, *Technol. Rev.* 73, 31 (1971).
6. P. B. Stone, *Japan Surges Ahead* (Praeger, New York, 1969).

Materials Supply: The Impact of Human Institutions

James Boyd

The industrial base of a modern technological society requires a vast array of raw materials, supplied in innumerable, constantly changing forms. This society provides its people with ample goods and services, only because it manages to secure adequate supplies of such materials as iron, steel, aluminum, copper, and phosphate. And contrary to recently proposed theories, the supply of these raw materials depends more on a succession of interrelated human institutions than on the resource base itself.

Throughout human history increasing numbers of substances have been discovered and more specialized needs have developed. These materials require reduction into useful states; they require mining or harvesting, concentrating, smelting, processing or refining, alloying or compositing, and fabricating before they become useful to society. Thus, sophisticated materials usage has mandated the formation of equally sophisticated human institutions; such an evolution formed the basis for the industrial revolution, which is still occurring.

Nature provides the basic resources; through a network of human endeavors and activities man discovers the needed minerals and converts them to the quality and form required by society. Man-made facilities produce the materials to meet the functional needs of society. Farms, harvested forests, mines, and oil wells do not spring "full blown from the brow of Jove." Rather, the basic resources that support the diverse materials-supplying activities must first be discovered through exploration. After discovery, they must be developed through such institutions as the capital market and corporations and through government policies. In the world of minerals, resources that can be converted, economically, into useful materials must be discovered and defined. Such resources, which form the foundation for economic progress, are termed reserves.

Reserves—circumscribed by location, quality, and economic viability—are finite. Further, they occur irregularly around the globe. Thus, no locality, state, or nation can be self-sufficient in all of the materials it needs or wants. Throughout history, this resource distribution problem has caused many wars. The development of transportation and trade has ameliorated but not eliminated this conflict in recent centuries.

Industry and consumers select and use materials on the basis of their ability to perform desired functions, and few desired functions cannot be performed by two, if not many more, different materials. The basic operation of society, therefore, does not depend on one or even several materials. As demands tax the ability of one commodity's resource base to supply all requirements, either new reserves evolve or more abundant materials emerge which can perform the required function. This process of supply involves continual dis-

The author is president of Materials Associates, 600 New Hampshire Avenue, NW, Washington, D.C. 20037.