

"Without further argument it will, we think, be admitted that the sciences are none of them separately evolved—are none of them independent either logically or historically; but that all of them have, in a greater or less degree, required aid and reciprocated it. Indeed, it needs but to throw aside hypotheses, and contemplate the mixed character of surrounding phenomena, to see at once that these notions of division and succession in the kinds of knowledge are simply scientific fictions; good, if regarded merely as aids to study; bad, if regarded as representing realities in Nature. No facts, whatever are presented to our senses uncombined with other facts—no facts whatever but are in some degree disguised by accompanying facts—disguised in such a manner that all must be partially understood before any one can be understood."

—*The Genesis of Science*, 1854

THE INTERDISCIPLINARY LABORATORY PROGRAM IN MATERIALS SCIENCES

By *Charles F. Yost and Earl C. Vicars*
Advanced Research Projects Agency

IT seems particularly timely to offer a broad discussion of the background and implementation of the Interdisciplinary Materials Sciences Program of the Advanced Research Projects Agency.* It is one which is unique in many respects and has attracted considerable interest within the scientific community. It is revolutionary in character, and there have been numerous inquiries concerning the program from the agencies of the government as well as from industry, research institutes, and university personnel engaged in or associated with materials research. Our purpose is to present some of the fundamental aspects of the program and to provide an insight from which the phi-

losophy, objectives, and implementation will become a coherent pattern.

The exact point in time that the interdisciplinary approach to the problems of materials science was born is difficult to ascertain, but it certainly evolved with recognition of the increasing importance and complexity of the science of materials. Important to this recognition were at least two events, and it is an interesting accident of timing that each was recognized at about the same point in time.

The development of the science of crystallography by mineralogists, the early realization of the atomic nature of matter by chemists, and the interest of metallurgists in achieving a scientific understanding of the effects of structure on mechanical properties of solids provided one of the unifying threads to the entire sci-

* This paper is confined to a discussion of the role of the Department of Defense in the Interdisciplinary Laboratory Program. It is recognized that other federal agencies have an interest in the program. The article is also being published in the *Journal of Metals*.

ence of solids. Another unifying thread not necessarily independent of the first, came with the discovery of quantum mechanics, its subsequent application to solids with the development of band theory approaches, and the more recent concentration upon imperfections of various kinds in solids. In the latter development, physicists have contributed the most quantitative and fundamental understanding of the science of materials. The deep appreciation which has been developing over the years of the relation between structure and properties has come about as the result of the efforts of many diverse investigations by physicists, chemists, metallurgists, crystallographers, etc., and there has been a growing awareness that the general advance in research on solids has come about because of a multidisciplinary approach. One evidence of this is the more widespread use of the words "solid-state science", implying a broader field or broader approach, than of the words "solid-state physics". The use of the word "interdisciplinary" is a natural consequence of the evolution of the science of solids.

Coincident with the recognition of the interdisciplinary concept, there came the acute realization that an increase in the support level for materials-science research was demanded in the national interest. It was recognized by a number of individuals who were at high government levels that basic materials-science information is a prime requirement in any sophisticated scientific effort involving weapons, space, and long-range atomic-energy developments. The materials-research effort carried out as a part of systems development is rarely meaningful and is much more expensive in the long run than a well-organized, long-range program which receives adequate support. It has been painfully apparent that there is no shelf of technologically available materials with unexploited properties meeting the requirements imposed by hostile environment. Solutions are sometimes found through a combination of design ingenuity and marginal materials properties, or a high-cost Edisonian crash program for a new material which is developed and pressed into service without full investigation of its properties. With the collapse of time which characterizes the increasing pace of technological advance, it has become evident that long-range programs in materials science are essential if we are to make fully effective use of available scientific and financial resources.

The Department of Defense has taken vigorous steps in discharge of its responsibilities in materials-science research with the establishment of interdisciplinary laboratories at universities. It would be well to consider for a moment the steps that led to the DoD program before discussing some of the detailed information associated with its implementation.

IN 1959, the Federal Council for Science and Technology established an Interagency Coordinating Committee on Materials Research and Development, representing the interests of the major federal agencies in this field. This Committee was composed of repre-

sentatives from the Atomic Energy Commission, the Department of Defense, the National Aeronautics and Space Administration, the National Science Foundation, the Bureau of Mines, the National Bureau of Standards, and the Bureau of the Budget. In their first report, the Committee members imposed upon themselves a major long-range task for the development of an adequate materials program, including aspects such as manpower, program areas, coordination, and funding levels. Significant within this report was the conclusion which approved in principle the establishment on university campuses of interdisciplinary laboratories for materials research. This report to the Federal Council for Science and Technology can be appropriately regarded as the genesis for one of the most far-reaching programs ever envisaged between the federal government and the scientific community.

Included in the report were other particularly noteworthy items which led conceptually to the Interdisciplinary Laboratories Program. Some of these were concerned with:

1. The need for increasing the output of personnel trained as physicists, chemists, metallurgists, etc., in the science of materials;
2. The existing practices of agencies supporting basic materials research in universities, which were not able to assure modernization of equipment and facilities;
3. The need for an immediate allocation of funds to reduce the equipment shortage in educational institutions and the encouragement of policies and practices to prevent a recurrence of the situation; and
4. Support for continuity of research funding for interdisciplinary laboratories on a long-term basis.

With these recommendations in hand, the Federal Council for Science and Technology, on April 28, 1959, asked the Coordinating Committee for specific proposals for the establishment of interdisciplinary laboratories for materials research on university campuses.

In response to this request, the Second Report of the Coordinating Committee on Materials Research and Development was submitted to the Federal Council on May 26, 1959. A survey of twelve universities was made in an effort to obtain a measure of the current effort in terms of PhD degrees per year and level of federal support; to determine immediate needs for new equipment and operating funds; and to estimate the expanded effort associated with an interdisciplinary laboratory, and the approximate number of PhD degrees per year which would result from this increased support. The universities chosen for this survey included those having the largest graduate programs in materials sciences, as well as a sampling of those having more modest programs. It was estimated that the twelve universities selected accounted for over half of the PhD's graduated in the materials field. Based largely upon the results of this survey, the Committee recommended to the Federal Council:

1. That the federal agencies undertake a long-range program to increase the output of PhD's in the materials field by approximately 75 percent. The program support

would be for immediate equipment needs, space, and operating costs.

2. That the Federal Council, as a group, promote policies which would allow individual agencies to carry out this program in an efficient manner.

The program outlined by the committee would, over a period of several years, increase the output of persons with PhD training in the materials field by a factor of about 75 percent. It would require an increase in the funding for basic research on materials by about \$21 million a year.

The Federal Council at its meeting on May 26, 1959, accepted in principle the sample program submitted and asked the interested agencies to determine which specific institutions they were prepared to support as part of an over-all national materials program. It was established that the program should be given high priority in view of the pressing and urgent research needs of federal agencies, especially the Department of Defense, the Atomic Energy Commission, and the National Aeronautics and Space Administration.

On June 19, 1959, the Director of Defense Research and Engineering, Dr. Herbert F. York, assigned to the Advanced Research Projects Agency responsibility for management of the Department of Defense portion of the program for establishment of university interdepartmental materials-research laboratories. An advisory group consisting of five members (one from each of the military departments, one from the Office of the Director of Defense Research and Engineering, and one from ARPA) was also established to assist ARPA in management of the program. In addition, a panel of non-government consultants was assembled each year to review critically, with the Advisory Group, each proposal, and to assist in preliminary screening of the program. The Advisory Group was charged with the following functions:

1. Assist in development of policies governing establishment and administration of the program.
2. Review budget plans for the continuation of the program and prepare recommendations for the Director of ARPA.
3. As necessary, review progress of the program.

The documentary record of the Interdisciplinary Laboratories Program was essentially completed by the statement of the President's Science Advisory Committee on May 16, 1960. Dr. Kistiakowsky, in commenting upon the report, said:

It is the Committee's conviction, as stated in earlier reports, that vigorous growth of basic and applied science in the United States is indispensable to the security and general welfare and to the growth of the national economy. The Committee further believes that the federal government must continue to have the central role in the support of basic research as it has in the recent past. Our report deals with one essential aspect of this role—the support of science in the institutions of higher learning.

The statement of the Committee singled out materials science as a large field which is vital to our safety,

and the interdisciplinary aspect is an important characteristic of that field.

With this background of broad program guidance and the assignment to ARPA of responsibility for management of the DoD program, two avenues were chosen as being clearly compatible with the over-all intent and far-reaching objectives which were cited by the Federal Council for Science and Technology and the President's Science Advisory Committee. These ARPA efforts are categorized as the Interdisciplinary Laboratory (IDL) and the Equipment Grant Program.

Selection Criteria

In developing criteria to be used in determining which universities should participate in the program, it was recognized that there were many facets to be considered in coming to an objective analysis which does justice to the many factors involved. At the outset, it was recognized that a strong faculty with a capability for accomplishing meaningful research in consonance with high standards for education must provide the framework within which this program could grow. The capability of the faculty determines not only the direction to be followed in conduct of research but also the thoroughness and accuracy which characterizes the results obtained. The interlocking of research and instruction in the classroom was considered a fundamental factor in the selection process. There are, of course, other benefits achieved through faculty reputation and capability such as the attraction that is offered to graduate students of unusual capability and promise. To complement effectively faculty capability and enthusiasm for the conduct of high-caliber research, a counterpart had to be demonstrated by the university management which recognizes, understands, and makes significant contributions to the efforts of the faculty in both research and educational pursuits. Oftentimes there are effective limitations to the extent that these efforts on the part of both faculty and management can proceed for budgetary and other material causes. It became one of the tasks of the Advisory Committee to look not only for the atmosphere which was conducive to research and education but to gain an understanding of the limitations hampering the progress that a university might be capable of making.

A great deal of new and important fundamental work in materials science has resulted and will continue to result from the intimate interaction between the several scientific disciplines. In certain of the schools, it was quite clear that significant steps were being taken to bring together various scientific disciplines by means of joint seminars, ad hoc committees from the separate departments for supervision of research, flexibility of curricula for postgraduate students, and the employment of the principle of dual departmental appointment for faculty members. All of these were important devices which, when coupled with a spirit of cooperation, coordination, and interaction of effort, enhanced the possibilities for greater productivity and sophisticated



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tion in research. On the other hand, it would be unrewarding to bring together all the materials research in process and force interaction where none logically exists. The effort proving most meaningful is that which creates an atmosphere and capability for interaction between the various scientific disciplines or improves this climate if it is in existence.

The rate of growth demonstrated by a university in the recent past became a significant criterion for several reasons. If a university attempts to move quickly into a position which requires large increases in number of faculty and graduate students, there is a serious hazard of its having to accept faculty and graduate students of lesser scientific capability in order to meet unrealistic goals. On the other hand, if a comparatively static situation was prevalent, one must question the interest and capabilities of the management and faculty in maintaining or working toward a strong position in the scientific community. Specific items which offered an indication of the growth pattern included university support being directed toward materials-science efforts in the form of faculty salaries, operating budget, and facilities; the amount of contract and grant support being received; the increase in number and quality of faculty members and graduate students; and the quality and quantity of publications.

There had to be, of course, an effort to establish some measure of the expected return on the DoD investment in terms of the program objectives. This is not simply a tabulation of the increased number of publications and graduate students that are promised, but rather an evaluation to be made on the basis of the probabilities of an orderly growth on the part of the university while maintaining high standards for research and education and developing the atmosphere for interaction between the various scientific disciplines.

Magnitude of the Chore

To illustrate the magnitude of the task of making a selection, in the first year of the program thirty-four universities submitted proposals totaling about \$150 million, and in the second year forty-two proposals were received totaling about \$154 million. After an initial screening, eight of the universities submitting proposals in the first year were visited, and out of this group three were awarded contracts. Twenty universities survived the screening process in the second year and were visited. Out of this group eight ultimately were awarded contracts.

These first two years were thought of as completing the implementation of the ARPA portion of the IDL program—at least for a period of three years or so, after which an assesment of the situation then prevailing could be made. But because of the somewhat peculiar circumstances of one additional university, as well as its unique and unquestioned qualifications to contribute to the over-all national objective, it was selected this year as the twelfth university to participate in the IDL program of ARPA.

Salient Features of the Contracts

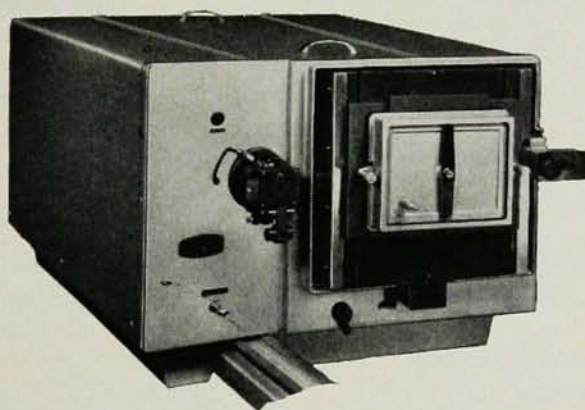
In consonance with the philosophy that guides the program and encourages a maximum of latitude with respect to the selection of problem areas and avenues of attack by the scientists and engineers in the program, the scope as described in the contract document is quite broad:

"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."

The IDL Program is intended to be an integral part of the total Department of Defense program in materials science and is planned to complement existing research programs now under way with the sponsorship of the Office of Naval Research, the Air Force Office of Scientific Research, the Army Research Office in Durham, N. C., and the other Service agencies. The broad concept and scope of effort of the interdepartmental laboratories will permit universities to fill the gaps in existing programs to achieve a meaningful and complete attack on the problem areas, as well as to follow promising avenues of work which develop as part of other projects but which would not be within the areas under contract support. One of the goals of the program is to achieve the maximum interaction between the IDL program and these other service programs. In meeting this objective, the continued participation of the Service representatives in connection with the management of the IDL programs becomes a vital link. At maturity, the total materials-science effort at a university will consist of the university-supported effort, ARPA support and Service support, other government agency support, and industrial support, each complementing and interacting with others to achieve the maximum gain with full utilization of personnel and equipment capabilities.

The ARPA program recognizes the need and provides funds to the interdepartmental laboratories for purchase of laboratory equipment needed for conduct of the materials-science effort. This is considered an important facet of the program since capability for meaningful research is becoming increasingly dependent upon the availability of modern equipment. For many years, the usual government research contract did not offer an opportunity to obtain more than a limited amount of equipment, and the research work was handicapped accordingly. Our discussions with many universities

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have revealed that this has been an almost universal problem and, in the interest of a balanced research effort, became an important consideration in the ARPA contract. Central facilities offering services to the program, such as crystal-growing equipment, electron microscopy, instrument and electronics shop, and drafting and photographic facilities, are also a part of the program. These central facilities would derive support from ARPA funds for use in the purchase of equipment and the salaries of trained personnel.

The opportunity for postdoctoral training is a prominent part of the ARPA program. It is felt that this is a most valuable period in a young scientist's career where further development and broadening can take place in preparation for greater professional responsibilities and independence in research. It provides him with a chance to work closely with a number of doctoral candidates, as well as senior scientists, and to gain in so doing from the professional aspects of this association. It is not a period for minor extensions of the PhD thesis, but rather is one which allows the scientist to enlarge his capabilities by moving into new materials problem areas. The postdoctorates chosen will be carefully selected and will offer considerable assistance to senior scientists at the universities in carrying out the enlarged research and educational responsibilities attendant on this program. It is expected that the number of people in this category will double in the next four years.

The space problem which has existed at most schools for a long time now becomes a controlling factor in their ability to carry out an expanded materials-science program. Accordingly, space is vital to the program. After considerable discussion, it was determined that ARPA would employ a use-charge principle allowing a ten percent per year recoupment by the university from the time the space is occupied until the construction costs will have been repaid in full, or until the termination of the contract. Financing costs incident to construction are not reimbursable by the government. Determination was then made of the appropriate amount of space required to house the ARPA program, and the cost per unit area. With regard to the buildings and their location on the various campuses, particular attention was directed to the geographical considerations which would foster the interdisciplinary concept. The optimum being sought is a location immediately adjacent to other science buildings or a proportionate part of a large building housing related scientific effort. By this contiguity, maximum utilization of the central and specialized facilities will be possible to support the interdisciplinary theme. It is interesting to note that in each case involving construction of a building, the universities have elected to erect larger buildings than amortized by ARPA.

The remaining factor of the ARPA program deserving special comment is the long-range funding provision provided in the contracts. This provision recognizes the fact that many of the scientific investigations to be undertaken will not be completed in a year or in any

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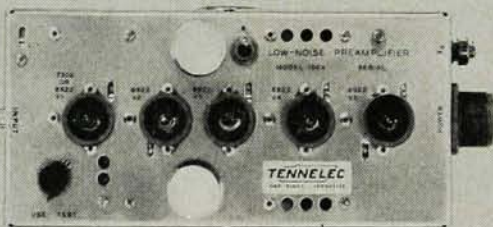
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short span of time. It is difficult, if not impossible, to separate some of the problems into finite groupings that can be accurately delineated in terms of time and effort. Instead, it seems infinitely better to attack the problem area with maximum utilization of the personnel and facilities available and take full advantage of broad flexibility to shape the course of the study and the time required to provide the solution. The emphasis as always must rest with the particular capabilities of the investigators rather than artificial milestones that are meaningless except to serve administrative purposes and involve all concerned in cumbersome and awkward attempts to anticipate the term of events. An annual review with each of the universities, more consultative than directive in its approach, is considered appropriate to the objectives of the total program. For these reasons the contracts are written to provide four-year support and are reviewed for renewal purposes each year, starting with the first year of the contract. By this means, the funding will be for four years in the future and allows adjustment to be made based upon experience gained during each year of the contract.

During the last three years, broadly written contracts have been negotiated with Cornell, the University of Pennsylvania, Northwestern, Massachusetts Institute of Technology, Harvard, Brown, Chicago, Stanford, and the University of Illinois. With the exception of Chicago, each contract provides for additional research space. In addition, contracts have been awarded to Purdue, the University of Maryland, and the University of North Carolina which are slightly more restrictive in nature than the first group but still provide the same kind of flexibility inherent in the larger contracts. There is no provision for expansion of research space in these latter contracts. Total initial investment for all contracts has been approximately \$34.5 million over a four-year period. Yearly renewal costs are estimated at the moment to be about \$15 million.

In addition to the Interdisciplinary Laboratory Program, 79 universities were selected during the past three years to participate in the ARPA Equipment Grant Program. This program provides for purchase of vitally needed equipment by universities working on DoD contracts to enhance the research under way in the materials-science area. A total funding of \$7.7 million was used to purchase equipment within this program.

This summation of the initiation of the Interdisciplinary Laboratory Program is not as complete in detail as many would no doubt like it to be. Nevertheless, it does cover the important features of the discussions, considerations, and actions leading to the establishment of the program. Furthermore, we regret that it has not been possible to acknowledge our appreciation of the participation of many individuals who gave unreservedly of their time and energies in helping to make such a program possible.

In another paper which is now in preparation, it is our aim to present views on the ideals, objectives, and management philosophies of the IDL program.