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DEPARTMENT OF THE NAVY
OFFICE OF NAVAL RESEARCH
875 NORTH RANDOLPH STREET
ARLINGTON VA 22203-1995

IN REPLY REFER TO
5720
22-35
November 18, 2022

Subj: FOIA REQUEST DON-NAVY-2022-005299

This is a final release to your Freedom of Information Act (FOIA) request received by the Office of Naval Research (ONR) on March 4, 2022 and given the number DON-NAVY-2022-005299. You requested the following Naval Research Advisory Committee (NRAC) reports:

1. Level of Research (1957)
2. War in the Nuclear Age (1958)
3. Basic Research in the Navy (June 1959)
4. BUWEPS study (1960)
5. Center for Naval Analysis (1963)
6. Comparison of Operating Philosophies of Science Boards (1969)
7. Comparison of Operating Philosophies of Science Boards (1969)
8. Use of DoD Facilities by University Investigations (1971)
9. VSTOL Ad Hoc Committee (1973)
10. Reflex (1973)
11. Laboratory Committee on Utilization of Computers (1973)
12. History of Navy R&D 1946-72 (1974)
13. Committee on Laboratory Utilization (1975)
14. Historical Perspectives in Long-Range Planning in the Navy (Sept 1980)
15. S&T Community in Crisis (May 2002)

Some reports were referred to the Secretary of the Navy (SECNAV) FOIA Office for release determination. There is nothing further you need to do at this time. If you need to contact the SECNAV FOIA Office you can reach them at: usn.ncr.dns.mbx.don-foia-pa@us.navy.mil. The following reports were referred:

1. Level of Research (1957)
2. Basic Research in the Navy (June 1959)
3. BUWEPS study (1960)
4. Center for Naval Analysis (1963)
5. Use of DoD Facilities by University Investigations (1971)
6. VSTOL Ad Hoc Committee (1973)
7. Laboratory Committee on Utilization of Computers (1973)
8. Historical Perspectives in Long-Range Planning in the Navy (Sept 1980)

Your request is granted in part and denied in part. We have located 393 pages that are responsive to your request. We are releasing 393 pages in their entirety. A search was conducted for the following reports and no records were found:

1. Comparison of Operating Philosophies of Science Boards (1969)
2. History of Navy R&D 1946-72 (1974)

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Washington, DC 20350-1000

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I, the undersigned, have been delegated Initial Denial Authority for the purpose of this letter. If you have questions, please contact the ONR FOIA Officer at (703) 588-2968 or Melissa.a.mills43.civ@us.navy.mil or. Please reference DON-NAVY-2022-005299 in any correspondence discussing this case. You may also contact the DON FOIA Public Liaison, Christopher Julka, at christopher.a.julka@navy.mil, or (703)697-0031.

Sincerely,

MELISSA MILLS
FOIA Officer

PLEASE RETURN TO:

Naval Research Advisory Committee
Room 0446, Main Navy
Washington, D. C. 20360

Volume I

A Report to the

Secretary of the Navy

on

Basic Research in the Navy

by the

Naval Research Advisory Committee

June 1, 1959

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Members of The Naval Research Advisory Committee

Dr. R. F. Bacher, Chairman, Physics Dept., California Institute of Technology

Dr. C. C. Furnas, Chancellor, University of Buffalo

Dr. T. K. Glennan, Administrator, National Aeronautics and Space Administration

Mr. E. H. Heinemann, Vice President, Douglas Aircraft Company, Inc.

Dr. R. A. Kern, Temple University Hospital

Dr. A. B. Kinzel, Vice President, Union Carbide Corp.

Dr. J. W. McRae, Vice President, American Telephone and Telegraph Company

Mr. G. Norton, President, Institute for Defense Analysis

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Dr. F. Seitz, Chairman, Physics Dept., University of Illinois

Dr. C. G. Suits (Chairman, NRAC) Vice President and Director of Research, General Electric Company

Dr. F. E. Terman, Provost, Stanford University

Dr. E. A. Walker, President, Pennsylvania State University

DEPARTMENT OF THE NAVY
NAVAL RESEARCH ADVISORY COMMITTEE
WASHINGTON 25, D. C.

IN REPLY REFER TO:

ONR:103:jg
Ser N-152
24 Apr 1959

My dear Mr. Gates:

The report transmitted herewith for your consideration marks a beginning of research on research in the Navy. We are fully aware that without development, production and operational training, there can be no effective fighting force. However, the current thinking with respect to research, and especially basic research as a Naval requirement, is much less clear and the relationships in this area have not been fully developed. This report begins to lay the basis for a clear expression of the requirement, bearing in mind that the success of the Navy in accomplishing its mission in competition with other world powers depends largely on a continuous flow of new and better weapons and techniques. This in turn, requires the continuous development of new technologies which have their roots in the results of basic research.

The report strongly supports the Navy's need for basic research. Only by active participation in a program for which it assumes a direct responsibility can the Navy insure a rapid flow of the products of new science from the laboratories of the Nation into the uses of the Service.

The Naval Research Advisory Committee believes that this report makes an appreciable contribution to a development of the understanding of the relationship of basic research to the missions of the Navy. However, we are acutely aware of many unsolved problems and we hope this report will provide the basis for further study.

The Committee urges that the Navy implement the recommendations of the Naval Research Advisory Committee, herewith presented.

Very truly yours,

C. G. Suits

C. G. SUITS, Chairman
Naval Research Advisory Committee

Honorable Thomas S. Gates, Jr.
Secretary of the Navy
Washington 25, D. C.

THE SECRETARY OF THE NAVY
WASHINGTON

24 JUN 1959

From: Secretary of the Navy
To: Chairman, Naval Research Advisory Committee

Subj: Report on "Basic Research in the Navy"

1. Having reviewed the Naval Research Advisory Committee report on basic research in the Navy, I would like to take this opportunity to congratulate the members of the Committee for their thorough and constructive analysis of the problem of basic research in the Navy. This analysis will be an important management aid in the proper administration of naval research programs.

2. The recommendations contained in the report will be very seriously considered and will be invaluable in our budgetary deliberations. I am sure, however, that the Committee is aware of the dangers which would attend fixing any part of the budget at an arbitrary percentage. I appreciate the opinions that basic research should be favored at this stage in our national affairs. At the same time, we must realize that our extensive national commitments require great care in maintaining a balance between the various portions of the total budget.

3. May I express the appreciation of the Department of the Navy for this pioneering cooperative effort. The special care and deliberation that has gone into the conclusions and recommendations of the Committee is apparent and recognized. The Naval Research Advisory Committee has rendered most effective and valuable service by producing this report.

W. B. Franke

Conclusions and Recommendations

of the
Naval Research Advisory Committee
concerning the report "Basic Research in the Navy"

This report sets forth the nature of basic research and its relationship to military end items. It establishes, by historical example and otherwise, the Navy's need for an increasing flow of basic research.

Basic research has played a tremendous role in the past, transfiguring the Navy by findings in such fields as radar, inertial guidance, missile propulsion, and atomic propulsion, and the accelerated pace of scientific progress in the last decade emphasizes its importance. The report points out that while the Navy can support only a small part of the total research of the world or the country, it must do enough in each area of interest to provide effective coupling and judgment for its own needs. It must also do that basic research essential to provide for its own direct needs in those areas of peculiar interest to the Navy which are not being adequately covered elsewhere.

In conducting basic research for either of these reasons, the investigators within the Navy Department must be constantly alert to recognize the impact of any findings on the needs of the Navy Department. These may not necessarily be related to the immediate objective of a given project but may well bear on the potential over-all position of the Navy. This is truly important. Time and time again, as brought out in the report, unexpected or even incidental findings have resulted in a major improvement in weaponry, communications, and the like. Said another way, only those engaged in basic research in a given area who, at the same time, have Navy interests at heart, are in a position to appreciate scientific findings of others and the significance of such findings to the Navy.

The report sets forth the judgment of those engaged in the direction and application of basic research in industry with respect to the level of basic research appropriate to the total Navy effort. Essentially this judgment is to the effect that the basic research effort in the Navy be approximately doubled in order to restore the former relationship of basic research to the total research and development effort. This would also bring the proportionate Navy basic research effort closer to that now current in those progressive industries operating in the areas of science and engineering.

The Committee concurs with the findings of the Arthur D. Little Study Group. It believes that this study lays the basis for detailed consideration of the basic research program required to fulfill the Navy's needs. However, it should be emphasized that this laying of the groundwork is but the first step in the process of rehabilitating the Navy's basic research program. In order to implement such rehabilitation a second step should be pursued forthwith.

The next step comprises the detailing of the program proper. Study of such detailing can be done well only by those who have a close working relationship in the Navy and with the scientific community, namely, the Office of Naval Research. It is recommended that this group prepare detailed programs in each of the fields of science related to the missions of the Navy as set forth on Page 49 of the report, plus such others as may be pertinent. In considering these fields it is obvious that certain items are the prime responsibility of the Navy; for example, oceanography. It is obvious that others are a major responsibility of the Navy; for example, meteorology, navigational phases of astronomy and astrophysics, marine phases of biology and biological sciences, the claustrophobic phase of psychology, and the like. Other areas are so broad that they are found wherever basic research is being done; for example, physics, material sciences, mechanics, electronics, mathematics, and the like. In these areas an effort sufficiently large to provide good coupling is needed. By setting forth specific programs pertinent and suitable to each of the areas in question and bearing in mind the foregoing, an over-all program can be prepared.

The approach just outlined is by no means novel, having been attempted more than once in the past. These attempts have not borne fruit because they consistently showed a requirement for total funds many times greater than contemplated at the time, and the principle of selection by areas was abandoned in favor of priority projects. To prevent this, after such a total program has been prepared by assembling detailed projects, a third step is in order. There must be another critical review still following the area distribution to bring the total cost within the augmented budget. If the budget augmentation is sufficient, i.e., double that of fiscal 1959, as herein recommended, the over-all program should approach the fulfillment of the needs herein set forth. Experience with the augmented program will show the success of the proposed approach and additional steps may be taken in future years, as necessary.

It is the Committee's recommendation that ONR proceed immediately with the studies outlined above and that a program corresponding to a doubled budget be prepared by the Office of Naval Research and be endorsed by the Secretary of the Navy.

Acknowledgments

By

The Naval Research Advisory Committee

The Naval Research Advisory Committee is pleased to acknowledge the capable efforts of Arthur D. Little, Inc., in the pursuit of a study of Basic Research in the Navy and the preparation of this report of the study under the direction of Vice President, Project Director, Dr. Bruce Old and his associates. In addition, we acknowledge the able work of the Navy's Training Device Center for the creation of the excellent graphics contained in the report. We particularly appreciate the effective work of the following deputies of the NRAC members who have provided continuous liaison and critical appraisal of the progress of the study for the Committee:

Mr. R. W. Larson	(for C. G. Suits)
Mr. G. M. Morrow	(for A. B. Kinzel)

As well as the able assistance of:

Mr. W. H. Doherty	(for M. J. Kelly*)
Mr. L. A. Cookman	(for E. R. Piore)

* Dr. Mervin Kelly was a member of NRAC at the time this study was undertaken, and he and his deputy contributed much helpful counsel and advice to the progress of the work. His appointment terminated prior to the completion of this report.

Volume I

A Report to the

Naval Research Advisory Committee

on

Basic Research in the Navy

June 1, 1959

Report Prepared
by

Arthur D. Little, Inc.

UNDER OFFICE OF NAVAL RESEARCH CONTRACT NO. NONR-2516(00)

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Summary and Findings

During World War II it became strikingly evident that scientific research is essential to the national security. The Scientific Research Board Report to the President in 1947 forcefully emphasized this point, stating:

> "The security of the United States depends today, as never before, upon the rapid extension of scientific knowledge. So important, in fact, has this extension become to our country that it may reasonably be said to be a major factor in national survival."

The Department of the Navy, fully cognizant of this trend, led the Federal Government in implementing changes in its organization and budget to reflect the requirements for expansion in scientific research. With the establishment in 1946 of the Office of Naval Research "to plan, foster, and encourage scientific research in recognition of its paramount importance as related to the maintenance of future naval power, and the preservation of national security," the Navy increased sharply the percent of its budget devoted to research.

Research in science and engineering is generally considered to consist of a continuous spectrum of activity having as its three major segments basic research, applied research, and development. Only by having a properly balanced and administered program at any given time in all segments can the rapid evolution of new weapons systems and techniques of warfare be reasonably assured. The most perplexing problem in achieving a properly balanced research program for the Navy is the establishment of an appropriate level of participation in basic research. There are two major reasons for this. First, there has been some lack of definitive understanding as to the nature of basic research and its role in the furtherance of the missions of the Navy. Second, substantial Government sponsorship of basic research is so recent a factor that policies are still in the formative stage. Therefore, at the recommendation of the Naval Research Advisory Committee, this study was undertaken to attempt to determine a basis for decision by the Department of the Navy in establishing proper levels of participation in basic research. Despite the obvious difficulty of this assignment, the potential usefulness of any quantitative findings in promoting future Navy effectiveness was thought to make the undertaking worthwhile.

For purposes of this study, the official Department of Defense definition of basic research was utilized. This definition, found to have broad acceptance by industry, university, and Government personnel, is as follows:

> "Basic research is that type of research which is directed toward increase of knowledge in science. It is research where the primary aim of the investigator is a fuller knowledge or understanding of the subject under study.". (Ref. DOD 3210. 1 Nov. 12, 1957)

The key question at the outset of this project was whether a necessarily broad definition of this type was interpreted in a sufficiently rigorous manner to permit the nation-wide collection of comparable and valid data on basic research policies, budgets, and expenditures from Government, industry, and university sources. This is a problem which has bothered the Congress and the Bureau of the Budget in the past. Considerable effort was expended in studying this matter, and it is gratifying to be able to report real progress toward clarification of this issue.

the output of all meaningful basic research is almost invariably represented by publication in the form of papers appearing in recognized scientific journals

The output of all meaningful basic research is almost invariably represented by publication in the form of papers appearing in recognized scientific journals. The infrequent cases of secrecy in basic research cause a delay in, but do not prevent, publication. This being true, if there is widespread consistency in the interpretation of what constitutes basic research, a correlation should exist between the number of people claimed to be performing basic research in Government, industry, and university laboratories, and the number of papers originating from each of these sources appearing in selected scientific journals. In the investigation of this assumption, data collected by the National Science Foundation were used to calculate the number of basic research workers claimed by Government, industry, and university laboratories, and the number of papers originating from each source was obtained by inspection of a selected sample of thirteen recognized scientific journals. A sufficiently strong correlation was obtained, between numbers of research workers and numbers of papers, to permit the conclusion that policy with respect to basic research definition and freedom to publish, is remarkably consistent nation-wide. On the basis of this important knowledge, it then became possible to collect with more confidence data from a number of sources for comparison of basic research policies, budgets, and expenditures. Furthermore, it was possible to make simple, rough checks as to reasonable validity of the data.

In the course of this assignment to assist the Navy Department in basic research policy formulation, three lines of attack were pursued:

a. Orientation

It became evident at the outset of the study that a broader understanding of basic research is a necessary step in evolving improved basic research policies. Therefore, much effort was devoted to the development of a concise and novel presentation, as given in this report, of the dependence of the Navy on technology, the nature of basic research, and the relation of basic research to the missions of the Navy.

b. Judgment and Analysis

People skilled in the art of administration of research were sought out in order that their experience and judgment as it might apply to the assignment could be used to advantage. This involved discussions with leaders in industry, in Government, and in universities.

New and extensive data on research and research personnel were collected and analyzed.

c. Quantification

A unique approach was made toward the synthesis of a mathematical model of the relationships between segments of the research process, in an attempt to develop a method for predicting proper levels of effort in each segment of the process.

Principal Findings

participation by the Navy in basic research in many fields is essential to the furtherance of its missions

Careful study has shown that participation by the Navy in basic research in many fields of science is essential to the furtherance of its missions. In this period of accelerating technological advance and dynamic international competition, national survival is largely dependent upon speed of acquisition and application of new knowledge. The vital role of basic research in accelerating progress is clearly demonstrated by a study of actual case histories, presented herein in the form of schematic models, and by an analysis of the research practices of leading corporations similarly faced with the problem of survival in this age of technology.

A dominant requirement of the Navy today is that of leadership in the development of new weapons systems and techniques of warfare in this period when rapid technological advance and international competition combine to render obsolete many weapons even before the production stage can be initiated. Such leadership can be maintained *with participation in basic research, scientists remain constantly abreast of the expanding frontiers of world science*

only by means of an aggressive, wisely conceived, properly balanced, and skillfully managed research and development program involving many fields of science. Essential to the success of such a program is effective participation in basic research, the life blood of the entire system of technological innovation. The basic research segment of the program is responsible not only for developing new knowledge, but also for communicating with the frontiers of science on a world-wide basis, and transmitting such knowledge or understanding to closely coupled applied research and development segments in order to maximize its utility. This vital function can be performed efficiently only by scientists actually participating in basic research and familiar with the needs of the Navy. With participation the basic research, scientists remain constantly abreast of the expanding frontiers of world science, and maintain the conceptual ability necessary to assist in evolving rapidly those applications vital to enhanced Navy effectiveness. Without participation, communication slows, the life blood is drained, and the over-all research program quickly deteriorates.

During the decade 1947 to 1957 leading corporations in high technological obsolescence rate industries have been far more aggressive in their participation in basic research than has the Navy.

While the basic research requirements of the Navy cannot be exactly compared with those of any other organization, the best available possibilities for comparison are found in technically based industries. Industry represents the second largest source of basic research funds. Many corporations have endeavored to evolve sound policies with respect to the extent of their participation in basic research in order to achieve that balance in their research and development programs most likely to guarantee corporate growth in the face of stiff competition in a period of accelerating technological advance. Information on research and development expenditures was, therefore, gathered from a number of leading technically based corporations. Excluded from the figures were Government contracts and those engineering activities not normally included in the research and development budget.

In 1947 the Navy allocated 10 percent of its research and development expenditures to basic research. This compared very favorably with the policies of many leading industrial corporations. However, a distinct divergence of policy occurred over the next ten years. Data from two of the most successful corporations in each of five technically based industries (chemical, petroleum, communications-electronic, pharmaceuticals, materials) showed these ten corporations in 1957 devoted 10-20 percent of their own research and development expenditures to basic research. The average allocation of 16 percent is in marked contrast to the Navy which currently allocates only 6-8 percent of its research and development budget to basic research.

Dollar figures add further confirmation. Information supplied by fourteen top corporations in these same industries showed that between 1947 and 1957 they tripled their total research and development expenditures and increased the basic research portion by a factor of 4.5. In the same period the Navy doubled research and development expenditures but increased the basic research portion by a factor of only 1.5. This increase in basic research expenditures was essentially offset by reason of the fact that the total cost per scientist increased approximately 50 percent during this same period.

A group of industrial directors of research familiar with the problems of the Navy were unanimous in their judgment that the Navy should increase the percentage of its research and development budget devoted to basic research.

To take advantage of the experience gained by industry in establishing corporate research and development budgets, we sought the opinions of leading industrial directors of research on Navy participation in basic research. The thirty-three men approached for opinions administer almost one half of industry's basic research expenditures and are responsible for allocation of funds within their respective corporate research and development budgets. Sixteen of the thirty-three believed they had sufficient knowledge of the Navy and its missions to be willing to express a judgment. Given the task of constructing a research and development budget for the Navy considering its missions, size, technical complexity, strength of Soviet competition, and the severe consequences which would be faced for being second best in national defense at this stage in history, it was the judgment of the majority that the resulting budget should show basic research in the range of 15-20 percent of the total research and development effort. An aggressive approach to participation in basic research is demanded, since nowhere is success more important today than in military technological advance.

the greater the technological strength of the competition, the greater should be the emphasis on basic research

In general, the greater the technological strength of the competition and the less immediate the probability of conflict, the greater should be the emphasis on basic research. Thus, under such conditions, the nature of weapons which might be used against this nation, and the countermeasures which might be employed, become less predictable, forcing a broadening of the basic research effort. Conversely, basic research plans can be more specifically drawn if conflict appears imminent.

Although there is legitimate widespread concern about a national shortage of scientific manpower, the Navy should find this no immediate obstacle should it decide to increase its basic research effort.

With any substantial increase in Navy participation in basic research, the problem of availability of competent scientific manpower will arise. At this moment it appears from a study of meritorious proposals turned down, or discouraged prior to submission, that sufficient manpower exists to expand the Department of Defense basic research effort in outside contracts by approximately 70 percent (omitting certain large capital equipment proposals). In addition, a rough approximation indicates an increase of about 10 percent is currently possible in the Navy in-house basic research effort. However, a serious manpower shortage may well develop in the near future as national research and development activities are currently expanding at the rate of 10 percent per year, whereas the number of scientists and engineers is increasing at the rate of 5 percent per year. At present approximately 25 percent of scientists and engineers are engaged in research and development activities, but only about 2 percent are engaged in basic research.

An expansion of the Navy basic research effort will place a premium on improved program planning and communications. The former might be achieved through greater use of scientists in a consulting capacity. The latter will require continuing study and emphasis since more than one half of the work performed will be outside of Navy laboratories and widely distributed geographically.

Because of the length of time required to evolve results, Federal budgeting for basic research presents special, and as yet not completely resolved, problems.

Budgeting for basic research is complicated by the necessity for planning on a long-term basis, while budgeting and operating on an annual basis. Planning basic research must take into account the time needed to form the research team, perform experiments and analyze and publish the results. The over-all time required for this process, as measured by the current average life of Office of Naval Research projects, is about 5 years.

Considerable progress in budgeting has been made through the availability of no-year money (available until expended) and advance financing of research projects. These tools are limited, however, by the amount of funds made available each year in the face of stiff competition offered by current fleet requirements particularly at times of expenditure curtailment or limitation. In order for the Navy to establish a more aggressive basic research program, methods must be found for budgeting and contracting on a basis which will tend to allow longer range planning and eliminate damaging annual variations. This is a problem of broad national interest, involving many agencies in addition to the Navy Department. The solution rests in large measure on bringing about a better understanding and appreciation of the role of basic research to provide the basis for coordinated budget planning by the Executive Branch and Congress.

It may be possible to develop a mathematical model of the relationship between segments of the research process that would aid in determining a proper level of Navy participation in basic research.

A program to develop a mathematical model of the relationship between the segments of the research process has shown enough promise to warrant consideration for further development. Results obtained by trying to fit a few actual case histories into the model as it now stands have been encouraging. However, more time is needed to substantiate the basic assumptions of the model, and the relation between what it predicts with respect to a proper level of basic research and what is observed in the real world.

Supplementary Observations

There exists within the Navy Department a general belief that the Office of Naval Research is the sole Navy office authorized to finance basic research. This misunderstanding stems largely from budget procedures, and has led to some confusion as to the extent of the Navy basic research effort. In addition, it has handicapped the administration of Navy laboratories in initiating basic research programs. Corrective steps and education are required.

Among Department of Defense laboratories, basic research contributions by the Navy laboratories are outstanding. This is especially true of the Naval Research Laboratory, which writes approximately 30 percent of all scientific papers originating in Department of Defense laboratories. The Naval Ordnance Laboratory, Naval Ordnance Test Station, Naval Electronics Laboratory, and others also make significant contributions. Knowledge generated in these basic research programs has contributed significantly to Navy effectiveness.

among Department of Defense laboratories, basic research contributions by the Navy laboratories are outstanding

This study is, so far as could be determined, the first of its type for the Government. In performing research on research, investigators are immediately confronted with the handicap of woefully inadequate data. With total research and development expenditures now amounting to approximately 6 percent of the Federal budget, more study of research is indicated. This is the path to improved national policies from which will emerge more effective utilization of our scientific resources. Some of the techniques developed or employed during the course of this study appear worthy of refinement and application by the Navy to such areas as:

a. *Research planning*

It should be possible to plan more effectively expenditures in basic research through detailed analysis of such factors as the so-called barrier problems within fields of interest to the Navy, and the relative world-wide research activity within such fields through literature investigations, coupled with study and evaluation of scientific manpower. Machine techniques and mathematical models may become useful in this regard.

b. Intelligence

Analysis of world-wide basic research activities by advanced techniques should offer excellent opportunities for progress in the field of intelligence.

Introduction

Ever since World War II, research has been increasingly recognized as a vital factor in the national defense. This has been emphasized in numerous studies since that time. However, only by a properly balanced and administered program of basic research, applied research, and development can the rapid evolution of new weapons systems and techniques of warfare be reasonably assured. A major unsolved problem is the determination of what constitutes a properly balanced research program at any given time in history. This is a matter to which attention must be directed if the United States is to carry out effectively its policy to deter war and to repel and decisively counter any possible attack.

The Department of the Navy has been aware of the essential role of scientific research in military preparedness. This is evidenced by the formation of the Office of Naval Research in 1946 (Public Law 588) and the vigorous programs of research and development carried out by this Office and the Bureaus of the Navy Department and Marine Corps since that date. A mechanism for continuing review of the Navy program was also provided in Public Law 588 through the establishment of a Naval Research Advisory Committee, to be composed of persons preeminent in the fields of science and research. The purpose of this Committee is to consult with and advise the Secretary of the Navy, the Chief of Naval Operations, and the Chief of Naval Research on matters pertaining to research and development.

In reviewing the research program of the Department of the Navy in 1957, the Naval Research Advisory Committee addressed its attention in particular to the problem of over-all balance. It was agreed that the most perplexing problem in connection with achieving a balanced research program for the Navy was the establishment of an appropriate level of participation in basic research. In the furtherance of its missions, it is evident that the Navy must undertake basic research, but the proper level of effort to be devoted to such work could not be clearly defined by the Committee despite extended discussions. At the same time, the importance of reaching sound decisions on this matter was recognized to be of great significance to the future capabilities and striking power of the Navy and Marine Corps.

As a result, the Navy Research Advisory Committee recommended that the Office of Naval Research enter into a contract with an outside agency to study this problem in detail. Accordingly on February 1, 1958, a contract was initiated with Arthur D. Little, Inc., having the following scope:

> Perform a study to determine a basis for decision as to the proper level of support of basic research by the Department of the Navy. Such a study is to be conducted through interviews, data collection, case histories, and other appropriate means.
>
> Prepare a report describing in detail the results of said study, and also prepare a monograph setting forth as clearly as possible the principal conclusions and recommendations resulting from the study.

Volume I of this report constitutes the monograph resulting from the study. Volume II, a detailed report with accompanying data and appendices, has been submitted separately to the Secretary of the Navy.

As far as could be determined, no formal study of this type has previously been published. The difficulty and complexity of the problem were apparent at the outset. Therefore, every attempt was made to take advantage of the suggestions, judgment, and experience of persons knowledgeable in the general field of research and its administration within Government, industry, university, and institute circles. The cooperation and response were excellent as the subject is one of great and increasing interest.

Navy Dependence on Technology— A Brief History

The First Congress authorized the Navy in 1789 to experiment on ships and guns. From the time of its formation in 1798 the Navy Department, in recognition of its dependence on technology, has been a leader among the armed services in conducting, financing, and encouraging research and development pertaining to its missions. This policy has had a profound influence on the continued gain in effectiveness of the Navy in all aspects of its operations.

While active research was going on in universities in Europe and the United States to increase fundamental knowledge, there was almost no organized research in industry in the United States prior to 1900. Its early activities thus placed the Navy in a position of leadership, and the technological advances of the Navy in its own mobility, firepower, communications, personnel operations, endurance, and supply had a great effect upon technical progress made in the civilian economy. The importance attributed by the Navy to its dependence on technological innovations is clearly evident from a chronological study made of its many contributions.* These range all the way from instigating the establishment of the National Academy of Sciences to the measurement of the velocity of light, the development of smokeless powder and the development of the aircraft carrier. The chronology includes such famous names as Fulton, Maury, Dahlgren, Davis, Michelson, Munro, Durand, Hunsaker, Taylor, and Sperry.

A New Era

Despite the great significance of early technological milestones in the development of a Navy second to none, they were abruptly paled into comparative insignificance by the advent of a new era. Simultaneously with the gathering of war clouds in Europe in 1939, there began a period

* See Volume II of this report for a Chronology of some 300 Navy historical technical milestones.

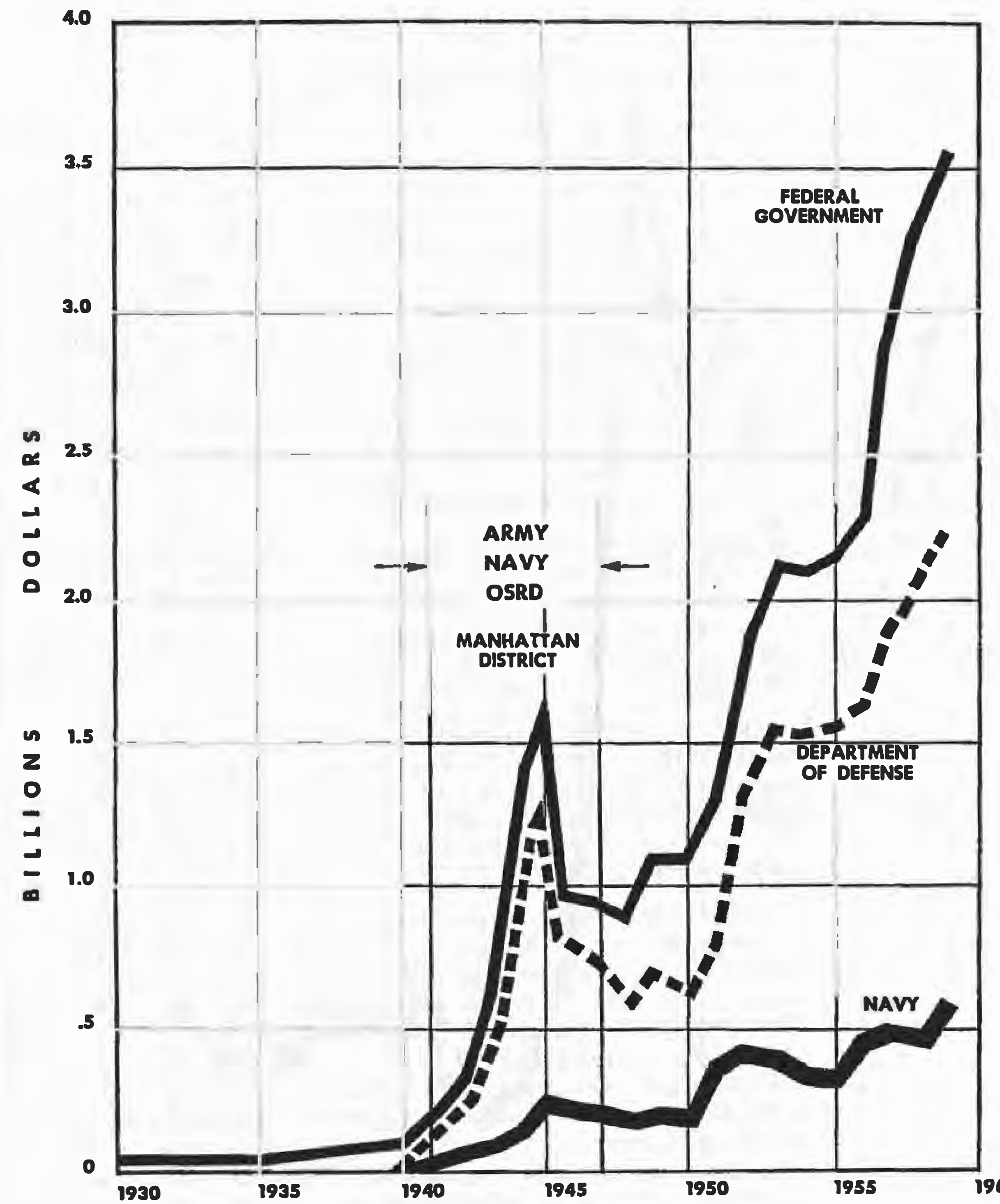
which will be known in history as the era in which science became a dominant factor in the determination of the military posture of the United States.

The birth of this stage of history was the direct result of actions taken by leading scientists. The two most important early steps involved direct contact with the White House in order to obtain the backing of the President. The first action was taken in the summer of 1939 by Albert Einstein, Enrico Fermi, Leo Szilard, and Eugene P. Wigner when they interested President Roosevelt, through Alexander Sachs, in the potential military importance of uranium. The President proceeded to appoint an Advisory Committee on Uranium under the chairmanship of Dr. Lyman J. Briggs, Director of the National Bureau of Standards. The Committee first met in October, 1939. At almost the same time Dr. Vannevar Bush, Chairman of the National Advisory Committee for Aeronautics, began to formulate plans for a National Defense Research Committee to:

> "coordinate, supervise and conduct scientific research on the problems underlying the development, production, and use of mechanisms and devices of warfare, except scientific research on flight"

Dr. Bush met with President Roosevelt early in June 1940, and an Executive Order establishing the new agency was signed June 27, 1940. Top scientists of the nation immediately volunteered their services and joined in organizing and directing the effort. The powers of Dr. Bush were extended June 28, 1941, by another Executive Order which created the Office of Scientific Research and Development and also placed under his direction research on military medicine. From a modest beginning in keeping with Government research expenditures of prior years, the NDRC grew in giant strides as the military contributions of science became obvious. Similarly the Advisory Committee on Uranium underwent major changes, the outgrowth of which was the rapidly expanding atomic bomb project of the Manhattan Engineer District.

The resounding impact on Federal research and development expenditures resulting from the aforementioned White House visits of 1939 and 1940 is shown by Figure 1. The era of scientific and technological impact on the national defense is clearly evident from the rapidly rising sums invested in this field. The many successes in increasing military effectiveness through such outstanding developments as radar, nuclear explosives, proximity fuzes, automatic fire control, rockets, guided missiles, jet aircraft, and numerous aspects of military medicine are well-known. Unlike the past, technological advances have become so rapid that many weapons systems are obsolescent by the time they reach the production stage. In order to preserve the peace, we find ourselves in an accelerating race of measures and counter measures, missiles and anti-missiles.



FEDERAL RESEARCH AND DEVELOPMENT EXPENDITURES

. . . . the impact of research for national defense

Figure 1

Rise of the Office of Naval Research

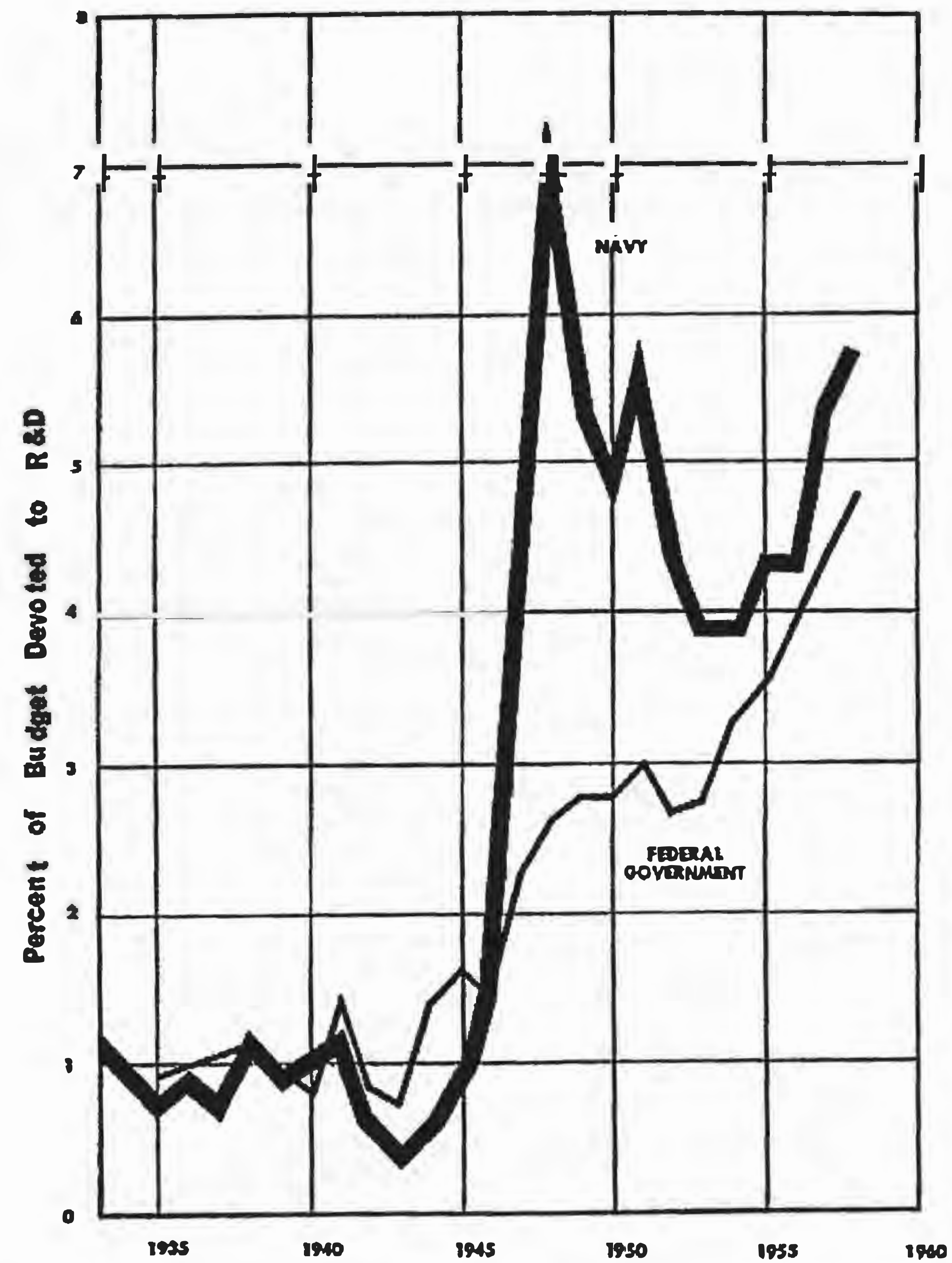
Throughout this era the Navy has continued its tradition of aggressive participation in research and development as shown by the growth in its expenditures (Figure 1). During World War II this growth was slowed by the absorption of technical manpower by the OSRD and the Manhattan Project. As the war neared its end, the Navy became alarmed at the possibility of a general exodus of scientists and engineers from research and development on subjects of interest to the Navy. A strong urge was quite naturally developing among them to drop everything of a military nature with the cessation of hostilities and return to their former peacetime pursuits. This possibility was disturbing, as the war years had taught top Navy personnel how essential it is to maintain close contact with the scientific world. Without such contact in a period of rapid technological change, they foresaw it would be impossible for the Navy to make the technical advances so necessary to the performance of its missions.

the war years taught top Navy personnel how essential it is to maintain close contact with the scientific world

Thus the Navy Department began early in 1944 to make new plans for the future. Conferences were held with top personnel in the OSRD and the armed services. Plans were initiated to establish a central office in the Navy Department which would foster research. It was as an outgrowth of these that the Office of Naval Research was formed in the Office of the Secretary of the Navy in 1946.

Great care was taken in establishing the policies of the Office of Naval Research with respect to the planning, negotiation, and administration of research contracts. The Navy then moved to allocate a much higher percentage of its budget to research and development. In this move the Navy took a substantial lead over the rest of the Federal Government (as shown in Figure 2).

In the planning of its early program, the Office of Naval Research had the assistance of many of the top scientists of the nation, most of whom were familiar with the long-range problems of the Navy because of their wartime experience. In general they urged that the Office of Naval Research place a large share of its budget in basic research. They pointed out that only a small percentage of the increasing expenditures shown in Figures 1 and 2 were devoted to basic research. They believed a change in this policy was essential to the long range military strength of the Navy as well as the nation. It was decided to rely on the judgment of these leaders in science. The Office of Naval Research placed as much as one third of its total funds in basic research and became a major national factor in this field. Many scientists credit this substantial post-war participation in basic research by the Navy, within its own laboratories and through outside contracts, for the current high stature of science in the United States. This pioneering effort made easier the entry of other



RESEARCH AND DEVELOPMENT PORTION OF FEDERAL BUDGET

. . . . the navy leads the trend

Figure 2

agencies such as the Army, Air Force, Atomic Energy Commission, National Science Foundation, and Department of Health, Education, and Welfare into basic research. In fact, the Office of Naval Research later transferred to these agencies contracts thought to be more closely related to their respective missions.

Basic Research — An Orientation

The research process is generally considered to be a continuous spectrum of activity composed of three major segments known as basic research, applied research, and development. The important roles of the applied research and development segments in evolving technological innovations are widely known to the general public. There are two main reasons for this. First, these are areas of research in which the Government and industry have long participated, so that the public has had time to learn of innumerable valuable contributions. And, second, when research has proceeded into these later stages, things begin to take shape. You can see and touch the new creations. They become newsworthy, and the public is kept well informed through aggressive press coverage.

the Federal Government did not begin to participate extensively in basic research until about thirteen years ago

But the basic research segment is different. The Federal Government did not begin to participate extensively either as a source of funds for, or as a performer of, basic research, until about thirteen years ago. Policies regarding administration and expenditures are still being formulated. The public has hardly had sufficient time to become familiar with this activity. In addition, many people believe they are incapable of understanding the implications of basic research, simply because it operates on the very frontiers of human knowledge. It is certainly true that knowledge of details in a particular field of science can be difficult, even for scientists working in related fields. However, such knowledge of details should not be confused with what is really significant for people to comprehend. It is far more important for the general public and Government officials, in this age of science, to acquire a broad understanding of the role of basic research in bringing about the advancement of technology. Such understanding is not difficult for the laymen to acquire, provided communications are clear.

The method to be used in this report to explain the nature and role of basic research is somewhat unique in that it will be partly diagrammatic. In this way it is hoped the primary objective of brevity can be coupled with clarity. In Chapters III and IV six diagrams, which we will call schematic models, will be presented to illustrate the following points:

> The manner in which, following the discovery of one significant new fact, a whole new field of technology evolves with time through basic research.
>
> The dependence of technological innovations of importance to the Navy upon the acquisition of knowledge through basic research in many fields.
>
> The explosive expansion of a new field through the influence and work of a basic research scientist and those inspired by his guidance or leadership.
>
> The importance to the attainment of effective technological progress of establishing and maintaining close coupling between basic research and applied research and development.

What is Basic Research?

It is logical to begin an explanation of basic research by trying to define what is meant by this activity. In this study the following official Department of Defense was utilized:

> **"Basic research is that type of research which is directed toward increase of knowledge in science. It is research where the primary aim of the investigator is a fuller knowledge or understanding of the subject under study."**

As is so often the case in trying to convey the meaning of a general concept, this definition may leave something to be desired. Nevertheless, it is rather widely accepted as a broad definition of basic research. It stresses the significance of permitting the basic research scientist freedom to consider any and all avenues as he seeks to create new knowledge or understanding of the subject under investigation. Since he is exploring the unknown, such freedom to probe and to change course is essential. But effective basic research requires much more than the interrogation of nature through theoretical and experimental study to discover new facts. It also involves ordering these facts into a pattern and communicating them unambiguously to others. This communication is achieved largely through the medium of papers published in scientific journals. Such papers represent the output of basic research. In general this is the only thing you can see or touch, the only tangible evidence emerging from the basic research efforts of a man or a laboratory.

Since most of these papers are highly complex, difficult to read, and their significance usually grasped only by a few other scientists, they

seldom receive the plaudits of the popular press. Yet these very same papers represent the basic building blocks, the new scientific knowledge, from which spring advances in the national welfare, economy, and military strength. These advances generally require some years to develop. This is because opportunities presented by basic research must be followed by the equally important applied research, development, and production phases before full fruition is realized. By this time there is a tendency to forget the contributions of basic research which made the entire advance possible in the first place. Its significance, difficult to recognize when first recorded in scientific papers, is further dimmed by the passage of time. Even the men who carried out the basic research may well be making their contributions in another field in a different location, and be no longer interested in or connected with the advance.

progress in basic research takes place in spurts or jumps

Progress as basic research takes place in spurts or jumps, recently popularly tabbed as breakthroughs. These spurts are by their very nature unpredictable. While most of them spring from soil already well prepared by prior work, some are accidental. Following the spurt there is usually a period of decreasing rate of progress until another one occurs. The gross characteristic of a plot of some measure of efficiency as a function of time will present a series of steps, with each vertical rise larger than that preceding, while the successive horizontal time intervals become shorter. By way of example, the development of projectile weapons from arm power using rock, spear, or boomerang; through mechanical devices such as bow and arrow, catapult, arbalest, or crossbow; then chemically propelled projectiles from hand and shoulder weapons through long-range artillery; then bomb-carrying aircraft; now missiles; and presumably the manned-satellite show such a development for the plot of progress as a function of time.

Another way of thinking about each spurt or breakthrough is that it opens up a new field of research. This field consists of a large number of facts, connected by some relationship to each other, and all unknown before the field is open. This situation is represented schematically in Figure 3 (a). While any one of the facts (represented by x's)in this field could have been discovered, it is typical that until the spurt no one thought of looking for them or thought it worth the effort to look. But once the field opens up, people realize in a vague way that facts are there and basic research is performed to find them. Knowledge is pursued for the sake of knowledge or understanding, and thoughts of application are usually latent. This is the phase in which Faraday was working in the new field of electricity when, on being asked of what use his work was, he replied, "What is the use of babies? They grow up!"

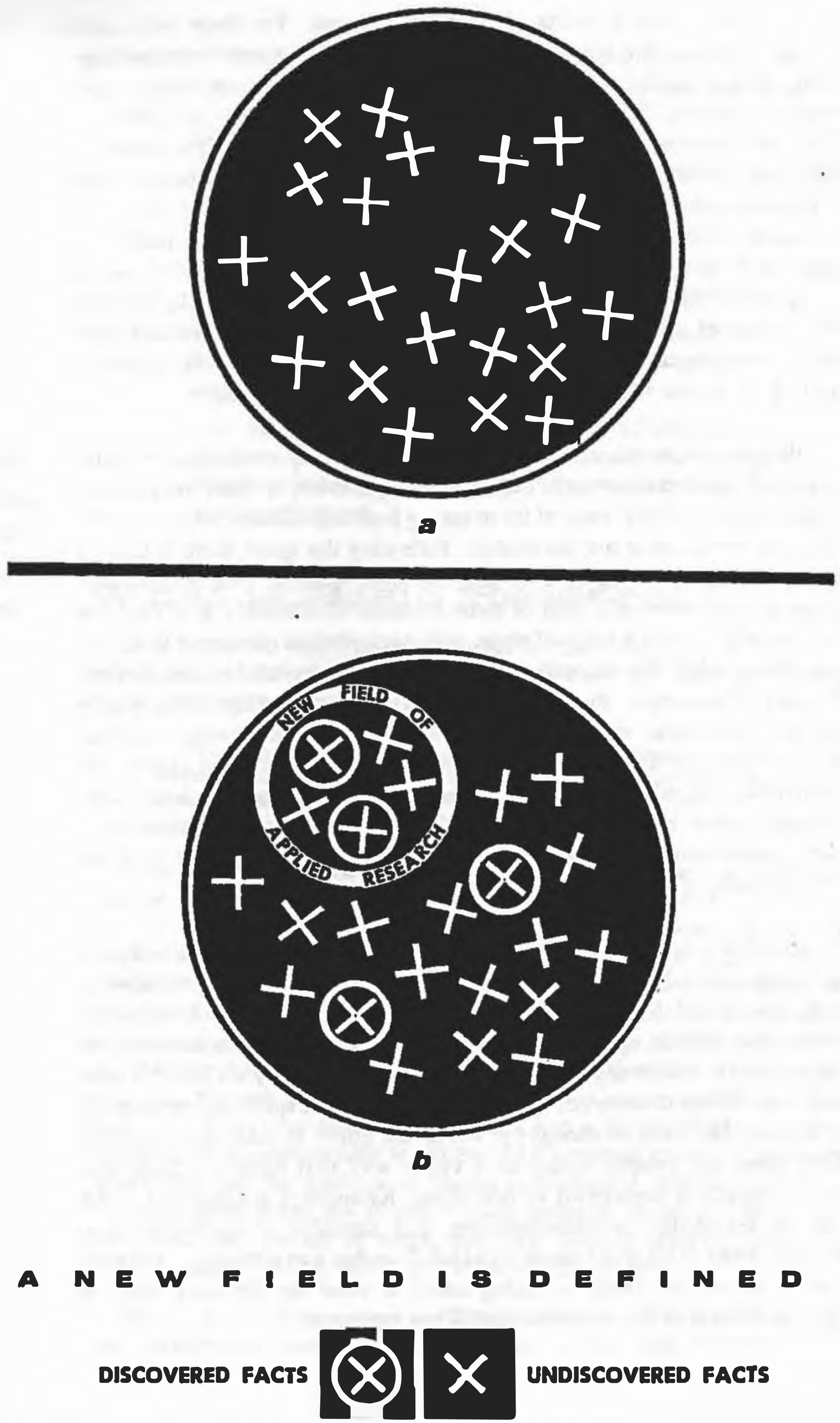


Figure 3

After basic research has been carried on for a time, the situation develops to that shown in Figure 3 (b). Some of the facts have now been discovered (represented by circled x's). These facts now known suggest that certain specific applications might be possible, particularly if suspected but undiscovered facts exist nearby. This is the origin of applied research which is impossible without the basic research which precedes it. Because it has a definite application in mind, applied research tends to concentrate in limited areas, indicated by the small dotted circle. By concentrating its effort in this way, it is apt to proceed more rapidly within the chosen area. On the other hand, basic research, which tends to explore the entire field, is more likely to find the fact which suggests a new application, or to discover a theory which immediately orders all the facts in the field into a pattern which then makes apparent numerous applications. Over-all concepts of this nature often involve understanding and assembling facts from several other fields of science.

the origin of applied research

From this generalized concept of basic research it is evident that this activity presents some publicity problems as far as exciting public interest is concerned. How, then, can this rather bleak scene be injected with a bit of fire and life? How can the initial segment of the over-all research process, so essential to our nation, be brought into proper focus to achieve public understanding? This is best accomplished by spotlighting a few examples taken out of the recent past.

The Shock Wave— A Case History

Our first schematic model will deal with the shock wave*. Many people are becoming familiar with it for the first time through the disturbances caused as jet planes crack the sound barrier. It has been selected as a model partly because it has received little other publicity and certainly cannot be classified as a shop-worn example of the value of research.

The soil was prepared for the discovery of the shock wave by earlier basic research work on the theory of sound performed by scientists from several nations such as Newton, d'Alembert, LaPlace, Lagrange, and Poisson. This field became the subject of discussions between two English physicists, Challis and Stokes, who were puzzled by certain problems in the solution of a mathematical equation, developed in 1808 by Poisson, describing flow in a gas. In seeking a unique solution, it was Stokes who in 1848 proposed that "a surface of discontinuity is formed, across which

*A shock wave is defined as a compression wave propagating relative to the fluid into which it advances and having reached an equilibrium state in which the steepening effects of inertia and the broadening effects of viscosity and heat conductivity are exactly counterbalanced, so that the wave is of constant shape.

there is an abrupt change in velocity and density." In 1860 this subject received further attention from two mathematicians, Earnshaw of Great Britain and Riemann of Germany. Working independently, they contributed significantly to the concept of the shock wave, Riemann developing new abstruse mathematical theories in order to do so. Then came Rankine of Great Britain and Hugoniot of France, who placed the subject of shock waves on a firm theoretical basis by correcting certain assumptions of their predecessors.

This brief story of the brilliant discovery of a new phenomenon is typical. At the time it must have been termed unexciting, vague, dreamy, and impractical. Certainly these six men could not predict the ultimate utility of their work, nor can we. But by 1959 the extensive and rapidly expanding basic research contributions, sparked by their initial efforts, have brought about over the years the development of things so diverse as to stagger the imagination. The multitude of present-day applications, many of importance to the Navy, are depicted in Figure 4. The ramifications of the work spread far and wide into such seemingly diverse areas as acoustics, explosives, jet engines, wind tunnels, rockets, satellites, underwater sound, solar physics, ballistic missiles, supersonic aircraft, and even thermonuclear devices.

But how did all of this come about? What happened between 1860 and today? The answer is that basic research performed throughout the intervening years has provided the additional facts required to permit subsequent applied research, development and production of numerous priceless technological innovations. As postulated in the general description of the research process, once the field of shock waves was opened up by Challis, Stokes, Earnshaw, Riemann, Rankine, and Hugoniot, then many basic research scientists explored for the facts. This involved scientists from many nations and many fields, principally physicists, mathematicians, chemists, and aerodynamicists. The work was performed in university, industry, and Government laboratories. Some of the key work was financed by the Navy Department. As facts emerged, scientific papers were written suggesting ideas to others, permitting cross-fertilization between sciences and the ordering of seemingly unrelated facts into theories. The field thus grows, first slowly, then at a rapidly accelerating rate. With all the interrelationships involved it is a most complex thing to picture. A schematic model of the history and development of shock wave theory is shown in Figure 5. Were all the side contributions of other sciences also shown, it would look even more like a large Chinese puzzle.

This complexity of growth is one of the interesting aspects of basic research. A seemingly remote fact may be the missing piece of a large picture puzzle, or its appearance in the scientific literature may trigger an important discovery. Once a fact is discovered and recorded, it is

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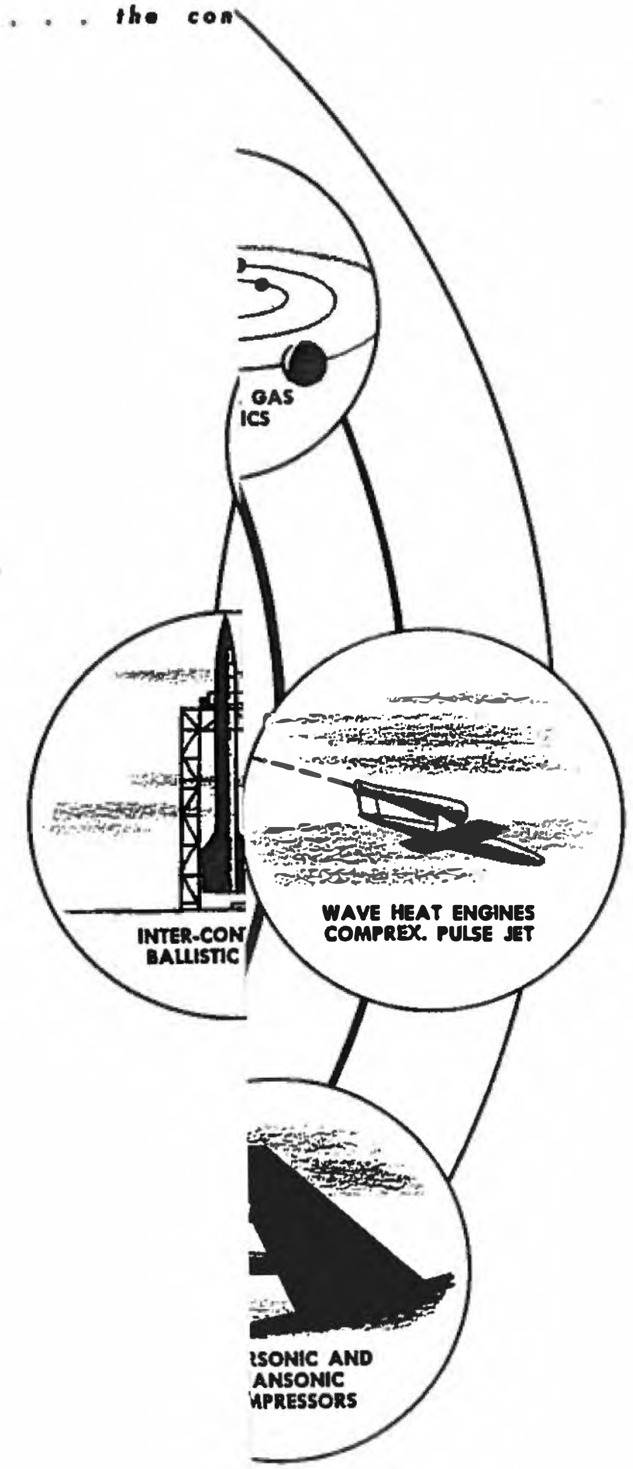

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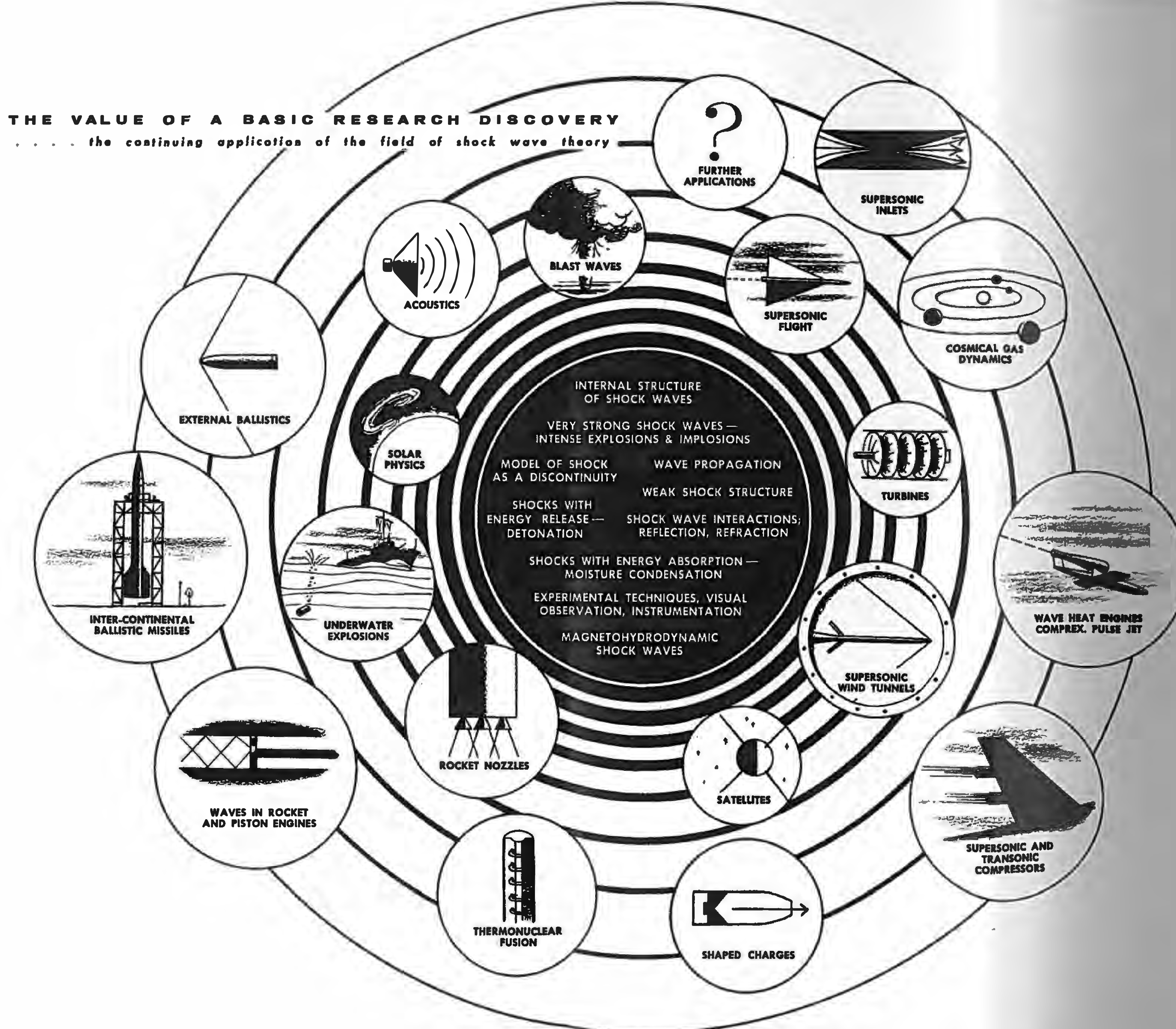


always there to use. Some are seldom used, others are used over and over again and the compound interest derived by man is almost beyond measure.

The question is often asked whether there are not cases where progress in a field such as this has been stalled because of lack of basic research. The answer is certainly in the affirmative. Yet, characteristically, it is difficult to foresee such void areas until after the fact. For example, one can state that progress in ballistic missile nose cones would have been more rapid if we had performed at an earlier date more studies of heat transfer phenomena in shock tubes. But the pioneering work in shock tubes was carried out at a time when the practicality of long-range ballistic missiles seemed quite remote. Thus one is equally free to condemn our lack of foresight, or to commend the Navy for its early participation in shock tube research (see Figure 5, 1950) which ultimately provided, albeit later than desired as we look back on it, the vitally important heat transfer information. What this really means is that a forward spurt by basic research in one field often exposes the need for basic research in the same and other fields. If we can be sufficiently foresighted to predict such things, much time will be gained. Study of the planning of research by a more systematic and thorough analysis of world-wide literature, scientific manpower evaluation, and by seeking out the so-called barrier problems in each field might well improve our abilities in this vital area. At a minimum, participation in basic research provides the Navy, as indicated by this example, the means to move rapidly at the moment the impact of a discovery in one field brings demand for knowledge from another field.

the performers of basic research

It is appropriate at this time to consider briefly the people who performed this work. They are anything but a collection of queer, long-haired, white-coated recluses, as science fiction would have us believe. Some are creative, some inductive, some cumulative and descriptive, some meticulous, and others routinely industrious — all types being essential to the growth of the field. Some remained in science all their lives, many as outstanding university professors. G. G. Stokes was himself the Lucasian Professor of Mathematics at the University of Cambridge, the chair once occupied by the illustrious Sir Isaac Newton. Some have become household words, such as Mach whose name is daily used in describing the speed of flying aircraft, missiles, and space ships. Many have remained essentially unknown. Others have become great public figures like Nobel Prize winning Lord Rayleigh of England and Dr. John von Neumann, the late member of the U. S. Atomic Energy Commission. Some like T. Von Karmann, G. B. Kistiakowsky, E. B. Wilson, and H. A. Bethe have devoted considerable time in recent years working at policy-making levels to enhance the technological strength of the United States. Others like G. I. Taylor, a brilliant and prolific contributor to science, found time to make contributions in completely different areas, such as the profitable invention of an anchor. Thus, the cross section of

Figure 5

The Shock Wave — A Schematic Model of the Development of a Field of Technology

The purpose of this schematic model is to show at a glance the typical manner in which, following its initial discovery, a whole field of technology evolves with time through basic research. Recorded on the chart are the major basic research contributions in the field of shock waves since its discovery in 1848.

Several general impressions are to be gained. Foremost is that the process of growth of a field of technology is complex. It has required the efforts over the years of numerous scientists from different nations. As shown by the mixture of colors and symbols, cross fertilization between fields of science is a necessary part of the process. Work builds on the achievements of the past, and accelerates with time as is evident from the growing density of work in recent years. Applications of vital importance to our national and military posture develop along the way with increasing frequency as already depicted in Figure 4.

The model is arbitrarily divided into five sections made up of research on shock tubes, explosions and detonations, magnetohydrodynamics, supersonic aerodynamics, and a central column devoted to continuing research in shock wave theory. There is considerable interaction between the sections, but cross-connecting lines have been omitted for purposes of simplification of the figure.

As shown at the top of the model, it all began in 1848 with the brilliant observations of two physicists, Stokes and Challis of England. Subsequent work by other physicists and mathematicians such as Earnshaw, Riemann, Rankine, and Hugoniot placed shock wave theory on a firm basis about 1890. From that time on, basic research in physics, chemistry, mathematics, and aerodynamics expanded the field at an accelerating pace.

Starting at the left, note that shock tube research was originated by Vielle in 1899. It was not until the work of Bleakney and co-workers in 1949 that the United States contributed significantly to shock tube research. The Navy actively participated in backing the work of Hertzberg and Kantrowitz at Cornell. This later led to studies of hypersonic flight at Mach 25, and is continuing to make important contributions to the intercontinental ballistic missile and space flight programs.

The first work on detonations and explosions around 1900 by Chapman and Jouguet concerned itself with combustion studies and propagation of flames. Much of the important work by people like Friedrichs, Kistiakowsky, and Von Neumann was performed under OSRD, Army or Navy contracts. Theories developed were utilized in the design of the first atomic bomb.

Magnetohydrodynamics is a relatively new field, having been opened up by Alfven of Sweden in 1942. Work is now rapidly expanding through the efforts of such men as Teller, Fowler, Spitzer, and many co-workers because of the interest in connection with nuclear fusion, solar corona, and various space age problems.

The development of supersonic aircraft is one of the most striking examples of the application of shock wave theory. This is an area of work in which basic research contributions of note have been made, beginning about 1900, by such men as Prandtl, Ackeret, Von Karmann, Taylor, Lighthill, and Lin. Other consequences of this work have been the development of nozzles, diffusers, and compressors for jet engines and rockets.

The central core research on better basic understanding of shock wave theory and structure has continued ever since 1848. Of late it has received the attention of an illustrious group of scientists such as Bethe, Courant, Chandrasckhar, Friedrichs, Taub, Weyl, and Von Neumann. What will next evolve in the way of startling new applications from the intriguing field of shock wave research is beyond our ability to predict. Meanwhile, active work in this field continues, with Government participation coming largely under the auspices of the Department of Defense, Atomic Energy Commission, and National Aeronautics and Space Administration.

people contributing to a field of basic research is one of remarkably diverse talents. But all have the common characteristic of insatiable desire to know and understand the universe in which we live.

The people who perform basic research have at least one other common characteristic — they are exceedingly rare in number. Almost all of them have doctorate degrees. And of the 2% of college graduates who obtain a doctor's degree in science, only about one in five combines the creative skill and the motivation in our present American society to remain in basic research. Finally, about one half of these have outstanding talents for this field as indicated by the fact that they produce some 80% of the resulting scientific papers. The United States today has a total of only about 27,000 basic research scientists, of whom about 15,000 are particularly active. Many wise people sincerely believe their contributions to our welfare are all out of proportion to their number. It is for this reason that there is concern over establishing policies to permit fuller and more effective utilization of those scientists now existing, and concern over increasing the number now being trained.

the United States today has a total of only about 27,000 basic research scientists

Strength in Science Indicated by Nobel Prizes

As a last point in connection with orientation of the reader with respect to basic research, the matter of recognition is worthy of mention. There are few public honors accorded basic research scientists in the United States. This is one reason the public lacks understanding of the importance of basic research. The highest international honor in basic research is the Nobel Prize, first awarded in 1901. While there are numerous causes and effects influencing the rise and fall of the strength of a nation, it is most interesting to note the distribution of Nobel Prizes in science by nation since 1901, as shown in Figure 6. Study of this figure provides one more indication why participation in, and effective utilization of, basic research is properly a question of grave interest to the Government of the United States.

NOBEL PRIZES IN SCIENCE

. . . an international measure of achievement in basic research

NATION	1901 1910	1911 1920	1921 1930	1931 1940	1941 1950	1951 1958
	P	E	R	C	E	N T
~~UNITED STATES~~	4	6	9	24	37	47
UNITED KINGDOM	17	16	23	19	21	20
GERMANY	33	40	32	24	16	7
FRANCE	21	16	9	9	0	0
RUSSIA	4	0	0	0	0	13
OTHER NATIONS	21	22	27	24	26	13

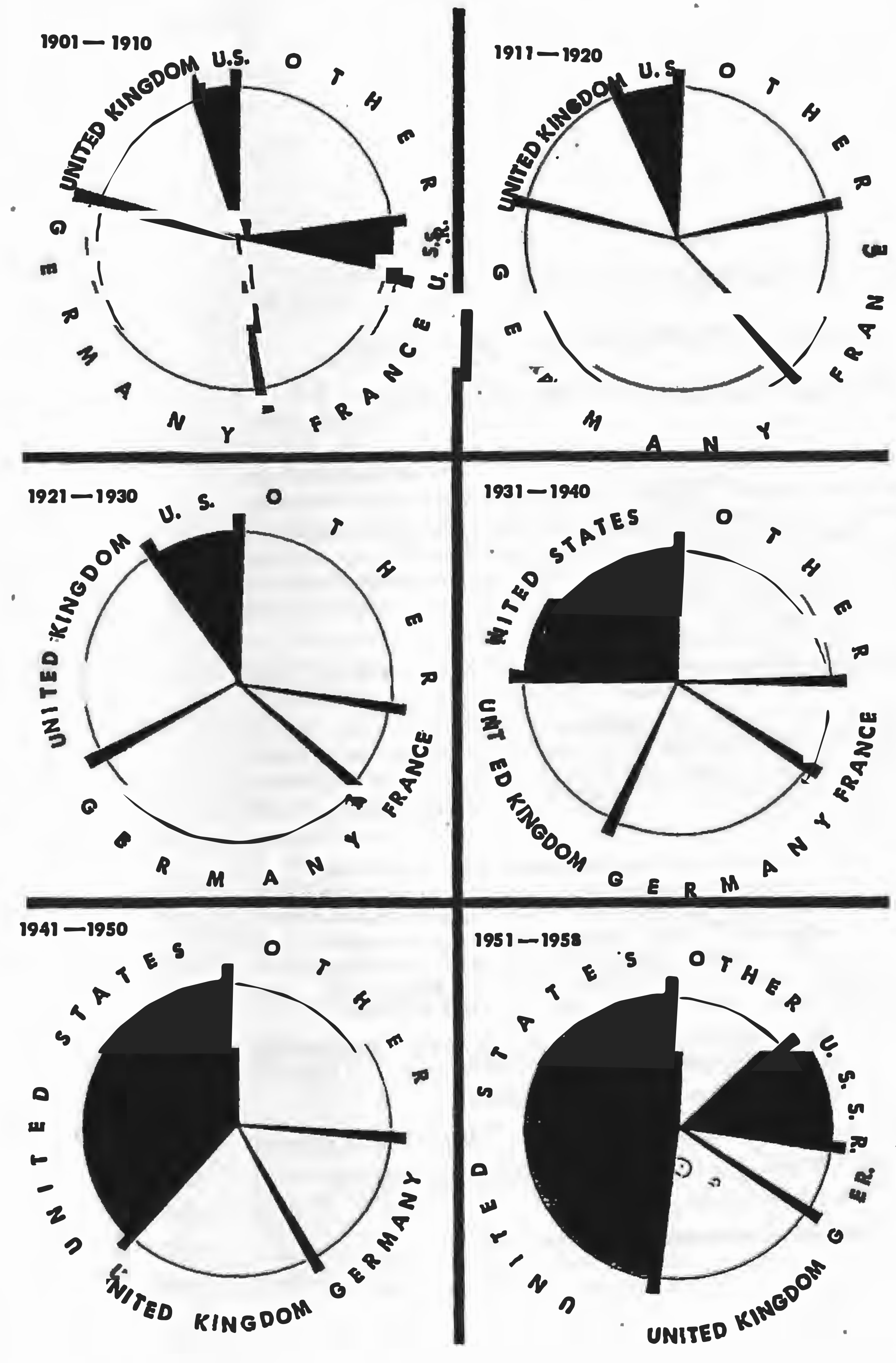


Figure 6

The Relation of Basic Research to the Missions of the Navy

The purpose of this section is to inquire into various aspects of the relation of basic research to the furtherance of the missions of the Navy. It is necessary to understand this subject before conclusions can be drawn regarding Navy participation in basic research. As will be seen, perhaps the key consideration in this period of accelerating technological advance is that of need for rapid and effective communication by the Navy with the frontiers of science.

The National Science Foundation, formed in 1950, has as two of its major purposes the promotion of basic research and education in the sciences. Nevertheless, continuing participation in basic research by the Navy was contemplated. This is evident in Executive Order 10521, on the Administration of Scientific Research by Agencies of the Federal Government, issued March 17, 1954, by President Eisenhower. It includes the following:

> "Section 4. As now or hereafter authorized or permitted by law, the National Science Foundation shall be increasingly responsible for providing support by the Federal Government for general-purpose basic research through contracts and grants. The conduct and support by other Federal agencies of basic research in areas which are closely related to their missions is recognized as important and desirable, especially in response to current national needs, and shall continue."

Thus, in order to evolve a basis for decision as to the proper level of participation in basic research by the Navy Department, it is essential that the missions of the Navy be clearly understood.

The missions of the Navy as now officially decreed are as follows:

Seek out and destroy enemy naval forces and suppress enemy sea commerce.

Gain and maintain general sea supremacy.

Control vital sea areas and protect vital sea lines of communication.

Protect shipping.

Establish and maintain local superiority (including air) in an area of naval operations.

Seize and defend advanced naval bases.

As pertaining to these missions, the Navy is charged with a number of functions including:

> "Conducting research and development, including the development of specialized weapons and equipment."

It has been shown in Chapter I that throughout its entire history, Navy effectiveness has been heavily dependent upon the advance of technology. There is no argument over the fact that the Navy Department must have the right to foster a vigorous program of research and development if it is to carry out its assigned missions. The point in question is the extent to which the Navy must participate in basic research in order to maximize the effectiveness of its research and development in the furtherance of its missions. Opinions on this subject vary considerably. The explanation lies, in part, upon a lack of understanding of the role of basic research in bringing about technological innovations of importance to the Navy. As a first step, therefore, it is desirable to expand upon this subject.

Perhaps the best method of determining the importance of basic research to the development of equipment and components of great value to the Navy is to study some actual examples. This can be done by selecting technological innovations and then examining in some detail the manner in which they came into being. For this report we have selected radar as an example of equipment and the transistor as an example of a component. Both are of proven military value. Radar detection of German aircraft has been widely credited with saving England in World War II, and it also revolutionized naval warfare. The tiny transistor is currently revolutionizing the miniaturization of various missile guidance and computer devices.

Radar — A Case History

. . . in research the only security is speed

History usually reveals that most great technological advances were the object of simultaneous investigations in a number of countries. Radar is a typical example in that we now recognize important work was proceeding in parallel in England, Germany, and the United States prior to World War II. It is positive proof of the fact that in research the only security is speed. Research in the United States leading ultimately to the development of radar, which revolutionized the means of detection of ships and aircraft, was begun at the Naval Research Laboratory in 1922.

On June 20, 1922, Guglielmo Marconi, the celebrated father of radio, in a speech in New York after accepting the Medal of Honor of the Institute of Radio Engineers stated:

> "As was first shown by Hertz, electric waves can be completely reflected by conducting bodies. In some of my tests I have noticed the effects of reflection and deflection of these waves by metallic objects miles away.
>
> "It seems to me that it should be possible to design apparatus by means of which a ship could radiate or project a divergent beam of these rays in any desired direction, which rays, if coming across a metallic object, such as another steamer or ship, would be reflected back to a receiver screened from the local transmitter on the sending ship, and thereby immediately reveal the presence and bearing of the other ship in fog or thick weather."

Shortly thereafter, while performing basic research on radio wave propagation, A. H. Taylor and L. C. Young of the Naval Research Laboratory obtained experimental confirmation of these speculations. Detection was made of a ship moving down the Potomac River. On September 27, 1922, a memorandum pointing out the possible Navy utility of such a detection system was transmitted to the Bureau of Engineering. The practicality of the idea could not be estimated at that time, and approval of a request to continue the work was denied. Interest in radio detection was renewed in 1930 at the Naval Research Laboratory when L. A. Hyland, during the course of experiments in radio direction finding, noted radio waves were reflected from aircraft which accidentally came within range. Again Taylor, Hyland, and Young were unsuccessful in obtaining funds to carry out a program of research in the field, as opinions of the practical importance of the work varied among both scientists and naval officers.

a creative idea is born in the mind of one man

A creative idea is born in the mind of one man. The idea which finally sparked the initiation of the radar project occurred to L. C. Young of the Naval Research Laboratory sometime in 1930. At that time, while studying transmitter key clicks, he made observations which led him to suggest that the pulse method of echo ranging (used in underwater depth finding) with radio frequency be applied to the detection of aircraft. After much preliminary thinking and calculating, a project was finally initiated March 14, 1934, and the first system was put into operation in December, 1934. While echoes from airplanes were observed, many problems remained. Applied research, having uncovered large areas of ignorance, had to await acquisition of new knowledge through basic research. Basic research work the first half of 1935 at the Naval Research Laboratory made it possible to predict the performance of radar receivers and transmitters. The results were applied to the design of a short time constant, fast recovery, non-blocking radar receiver, and a self-quenched, high-power radar transmitter. A team consisting of R. M. Page and R. C. Guthrie, with help and suggestions from others, then succeeded on April 28, 1936, in putting together equipment which gave satisfactory echoes from airplanes at ranges up to twenty-five miles.

But, as important as was this portion of the development of radar, there was much vital basic research work which had both to precede and to follow before radar could become of military importance. A reasonably complete diagrammatic model of the history of radar is shown in Figure 7. It is a convincing presentation of basic research contributions to the development of aircraft and ship detection systems vital to furthering the missions of the Navy. Further, it is an example of the importance of Navy participation in and coupling with world-wide basic research. Finally, it illustrates successful national and international cooperation in research and development. Numerous contributions were made by the British under the leadership of Sir Robert Watson-Watt, by several National Defense Research Committee laboratories, by Army laboratories, and by several companies in this country such as the Radio Corporation of America, Bell Telephone Laboratories, General Electric, Sylvania, Westinghouse, Raytheon, Philco, and Western Electric. As is so often the case, the knowledge and techniques coming out of the work on radar have made significant contributions to other areas such as communications, computer circuits, scientific instrumentation, television, meteorology, navigation, air traffic and missile control, and radio astronomy.

successful national and international cooperation

The Transistor — A Case History

The transistor, the second example chosen for study, is a recent important spurt or breakthrough in the already exciting field of electronics. This field owes its genesis to the development of the vacuum tube, which permitted amplification of electrical signals. Since World War II it has blossomed into a $7.6 billion industry. Currently, it is being revolutionized by the transistor. This pinhead size wafer of germanium or silicon and its twin brother, the semiconductor diode, perform an ever-increasing number of the functions of the electron tube. With the development of subminiature associated components, they permit electronic systems to be reduced to about one tenth former size. In addition, they require far less power and in their maturity promise trouble-free operation for decades. Recently transistors allowed transmission of the President's Christmas message from a satellite in outer space. Potential civilian and military uses are legion.

While the transistor was invented at the Bell Telephone Laboratories in 1949 by Bardeen and Brattain, working with Shockley, its origins go back at least to 1874, when the phenomenon we now call semiconduction was first observed. The next major step in the development of the transistor came as the result of basic research on electrical conductivity in metals. The knowledge gained was extended by A. H. Wilson into the study of why some materials like selenium, silicon, copper oxide, and silicon carbide conduct electricity about a billion times better than many insulators and only one millionth as well as metals. This work led in 1931 to modern semiconductor theory, the foundation from which grew the transistor and many other important discoveries.

However, the path was not direct, nor was it simple. Materials 99.9999999% pure had to be made — and a great deal of research went into that. Crystals of high chemical purity had to be produced. The role of surface layers one molecule thick had to be understood. Experiments led to revised theories, and better theories to more refined experiments.

The research effort, in retrospect, was world-wide. Workers from England, France, Germany, Holland, Russia, Spain, and the United States all contributed. In the United States, military research during World War II and basic research, partly military sponsored, at M. I. T., Stanford, Pennsylvania, and Purdue contributed significantly. Techniques, tools, instruments, and isolated facts coming out of the vast atomic energy program also aided the cause. Thus, the transistor did not just happen — the soil was well prepared for the superb, Nobel Prize winning effort of the three Bell Telephone Laboratory scientists. This complex triumph of the inquiring mind is shown in schematic model form in Figure 8. Navy coupling to this field permitted more rapid application of transistors to many pieces of equipment of importance to the Navy.

Importance of the Competent Man

In those fields of science of greatest potential relevance to the missions of the Navy, the surest path to progress in basic research is to secure the services of the most competent scientists within the field. Heavy reliance must be placed upon their judgment. Often they are the only ones possessing the vision or the curiosity to suggest initiation of research projects necessary to the creation of certain new and useful facts. Navy awareness of the importance of seeking out top scientists for participation in its basic research program has proven invaluable.

The rate at which the competent man can contribute to science multiplies rapidly through his guidance and influence on his associates. That this rate can become amazing is shown in our next schematic model, Figure 9. Here is traced the influence on a field of science by I. I. Rabi, one of the many competent scientists selected for support by the Office of Naval Research.

the rate at which the competent man can contribute to science multiplies rapidly through his guidance and influence on his associates

The early work of Rabi and his associates was in molecular beams. At the time this probably seemed remote from any Navy interest. But the inspiration of Rabi and the training he and his associates imparted in basic research and certain experimental techniques were shortly to prove invaluable. Upon the outbreak of World War II Rabi drew many of his students and associates, such as Zacharias, Purcell, Nordsiek, Millman, Schwinger, Kellogg, Kusch, and Ramsey into the M. I. T. and Columbia Radiation Laboratories and proceeded to spearhead the spectacular

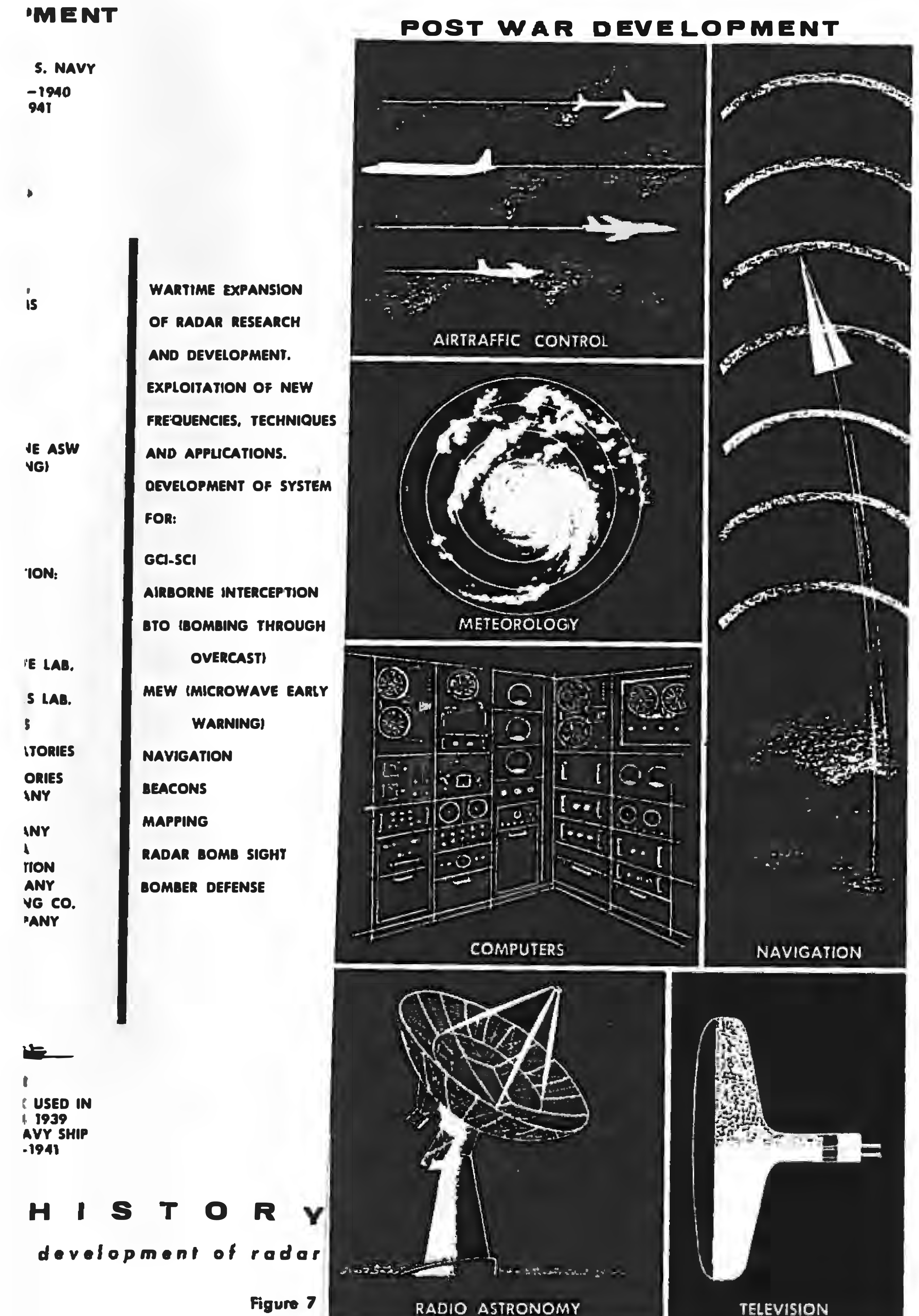


Figure 7

growth of microwave radar. Following the War, with the influx of new apparatus and techniques developed, and a group of new students and associates, the work spread into many new areas. Already the basic work of these scientists is bearing fruit in such fields as improved DEW line early warning, missile guidance, and radio astronomy systems. However, the payoff to the Navy from investment in Rabi and associates goes far beyond this. The contributions of the men who appear in one branch or another of Figure 9 are so numerous as to defy estimate. People like Alvarez, Bloch, Estermann, Kellogg, Purcell, Rabi, Ramsey, Townes, Van Vleck, Zacharias, and many others have been instrumental, through service to the President, the Department of Defense, and the Atomic Energy Commission, in the formulation and execution of countless research programs and policies for increasing the naval and military strength of the nation.

The Requirements for Coupling Between Segments of the Research Process

It is now evident that basic research plays an important part in evolving new weapons systems. But why should the Navy have to perform basic research? Why not let the National Science Foundation, or some Department of Defense office, especially established for the purpose, perform all the basic research for the Navy? These questions were often asked during the course of this study. It was the unanimous opinion of leading research directors that so long as there is a Navy with missions as now assigned, it is essential that the Navy participate in basic research. Let us examine the main reasons for this opinion.

it was the unanimous opinion of leading research directors that so long as there is a Navy with missions as now assigned, it is essential that the Navy participate in basic research

An organization which operates in a field dominated by technological obsolescence must have a research and development program if it is to survive. In such a situation the basic research segment of the research process cannot be looked upon as a luxury item which can be separated or cut off at will. On the contrary, it is the life blood of the entire research and development process. Through the circulation of the knowledge and understanding it develops or acquires, basic research is the major coupling force of the process. This is shown diagrammatically in the schematic model in Figure 10. Rapid and effective transmission of new knowledge throughout the over-all program requires the presence of basic research scientists. It is not only their function to develop the new knowledge upon which technological advances are based, but also to acquire additional new knowledge by communication with science on a world-wide basis. It is only they who can understand the work of others who also explore the boundaries of science. It is only they who can seek out through personal contact and through study of world literature the significant new

Figure 8

Basic Research Necessary to the Development of the Transistor

A Schematic Model

The purpose of this schematic model is to illustrate the vast amount of basic research required before it became possible to develop the transistor, a breakthrough of great importance to the Navy in the miniaturization of countless reliable and rugged weapons systems components.

The chart is divided into five rows. The central black arrow represents the main stream of transistor research. The other four rows represent contributing areas of research, all of which were necessary to the continued progress of the main transistor stream. Note in particular the many interactions between techniques, materials research, empirical development, experimental tools, and theoretical work carried out by numerous scientists from many nations before the groundwork was completed for the birth of the transistor.

The earliest semiconductor work dates from 1874 with publications on the electrical properties of lead sulfide, silicon carbide, copper oxide, and selenium. By 1936 a flourishing business of semiconductor power rectifiers existed. However, these developments were largely empirical and could not possibly, of themselves, have led to the transistor. Theoretical guidance and direction from basic research was necessary.

The transistor requires single crystal materials of a chemical purity unattainable twenty years ago — one copper atom in ten billion germanium atoms produces measurable electrical effects. The basic research which permits attainment today of 99.9999999% purity crystals on a commercial scale began with Volmer in 1922. Continued by many investigators, as shown, it led to new concepts of crystal growth, lattice defects, and dislocations, and to the very recent triumph of Dash in the production of dislocation-free silicon single crystals. Simultaneously, the development of ultra-refined chemical analytical tools assisted in the attainment of the crystal purity required.

The development of semiconductor physics began in 1928 with work on the quantum mechanical theory of solids and metals. By 1931 A. H. Wilson brilliantly applied the methods of band theory of metals to formulate the first modern theory of semiconductors. Within a few years Mott and others applied Wilson's results in the development of theories of electrical rectification. The silicon diode was then developed at the Government-supported M. I. T. Radiation Laboratory, following the metallurgical and chemical researches on silicon crystals by Ohl at the Bell Laboratories.

Basic studies on the mechanisms of conduction in semiconductors at the Bell Laboratories and at Purdue, under Navy contract, and basic research on the behavior of semiconductor surfaces at Bell, were the milestones of 1944-48. Finally, in 1948 the first experimental point contact transistor was made by Nobel Prize winning Bardeen and Brattain of Bell. Four years later the theory of the p-n junction was worked out by Shockley (a Nobel Prize winner), and shortly thereafter, Teal and Sparks, also of Bell, made the first junction transistor.

The first devices were fragile, noisy and little more than laboratory curiosities. However, the potentialities of the development so captured the imaginations of scientists that further research was stimulated to a degree seldom paralleled. Transistorized devices are being developed in staggering numbers for both military and civilian use. And soon we will see growing out of the end of this schematic model a whole new series of developments influenced by the knowledge gained — developments in such fields as direct conversion of thermal energy to electrical energy, electronic refrigeration, electroluminescence, parametric amplifiers, solid state masers, and others not now foreseen.

facts appearing on the endless frontiers of science. And it is only they who can transmit the vital information to applied research and development personnel in such a manner as to maximize its utility. This function cannot be performed by liaison men, who quickly lose touch in the rapid march of science, but only by those who continue to participate actively in basic research. The realization of these important facts during a period of accelerating pace in science is the major reason for the growing emphasis on basic research in all the leading industrial research laboratories in the United States (data will be presented in Figure 11).

It is clear that participation by the Navy Department in basic research is essential. Such participation is not "wasteful duplication" on the work of others in industry, universities, or Government. Just the reverse — participation in basic research by each Government department makes more useful the work of every other department. Rapid and effective communication in basic research has cut to a minimum unnecessary duplication. Any duplication is usually undertaken deliberately to corroborate or dispute the results of others. Even then, the method of attack on the same problem by two basic research workers is seldom identical.

participation in basic research by each Government department makes more useful the work in every other department

Time becomes the ruling factor in any race. The present technological race with the Soviet is no exception. To minimize the time cycle from new concept to production of weapons is the primary requirement of national defense today. To accomplish this requires a balanced research program with proper emphasis on, and close coupling between, basic research, applied research, and development. A Navy which failed to participate in basic research in this age would first find itself unable to communicate with the expanding forefront of science, and then find itself unable to evolve the radically new systems which make possible survival.

Supplementary Benefits of Navy Basic Research

The supplementary benefits accruing to the Navy from participation in basic research are centered in research planning and in manpower.

Stemming from the careful initial selection of competent scientists to work on projects in fields related to its missions, the Navy has reaped a growing harvest. Many of these men have become interested in the problems of the Navy to the extent that they might be considered a scientific reserve. They participate extensively with Navy science administrators in the planning and evaluation of research programs; bring to the attention of the Navy interesting projects, and useful results obtained by colleagues; and help single out the bright young scientists who will constitute the leaders of tomorrow. The cooperation developed has also allowed Navy liaison men to perform more effectively their work of seeking out promising projects and scientific information the world over.

Figure 9

The Scientist's Contribution to the Growth of a Field

The Influence of I. I. Rabi

Most directors of research agree that the best method of achieving progress in basic research in a field of science relevant to one's missions is to select a scientist competent in the field, and give him wide latitude as to choice of project and methods of attack within an agreed upon budget. This is because the competent scientist is likely to be the only one capable of visualizing the best means of carrying out the basic research necessary to the discovery of important new facts. This in turn means that during the course of the work there are liable to be individual projects which seem quite remote from one's missions. Thus, the research administrator is sometimes challenged for justification of expenditures of funds, especially if public funds, for certain projects. Here is where sound judgment and patience must be exercised so that a proper decision may be reached.

Let us attempt to shed some light on the importance of selecting and backing the competent man by means of a schematic model of an actual case history. The purpose of the model is to trace the extensive contributions to, and influence on, the growth of a field of science over the years by an outstanding basic research scientist working with wide latitude. We have selected I. I. Rabi as the individual for study. He has worked on projects which often seemed at the time to be remote from the missions of the Navy. He has worked sometimes under Navy or Government contracts. And, finally, he has made contributions of great value to the Navy.

The schematic model depicts Rabi as the central figure in the growth of the fields of molecular beams and magnetic resonance, together with those who inspired him, his students, his students' students, and his associates. Short descriptions of important basic research contributions are accompanied by the names of contributors and dates. For the sake of brevity a number of omissions have necessarily occurred, so that the model should be viewed as being illustrative rather than exhaustive.

Rabi's work and influence can be pictured as a rapidly growing and expanding tree. It has as its roots the molecular beam work of Prof. Otto Stern of Hamburg University, who first inspired Rabi while the latter was a student there in 1929. The trunk of the tree consists of the further work of Stern and associates, and Rabi and associates in his laboratory at Columbia in the Thirties. The branches represent the tremendous spread of developments to magnetic resonance and allied fields following World War II. (As already noted elsewhere, during World War II Rabi and many of his associates made valuable contributions to microwave radar development at M. I. T. and Columbia.) Many of the branches were directly influenced by Rabi and collaborators and students as indicated by the black and white symbols. Others, such as Bloch and Gorter, were independent contributors as noted by the green color. Work participated in by the Navy is designated by the violet color. A further interesting and important point is that six Nobel Prize winners appear in the model — Stern, Rabi, Bloch, Purcell, Lamb, and Kusch. Rabi, as the central figure, has brought to this field of science a maturity which has left a permanent imprint on world-wide science and technology.

The widespread and growing contributions of Rahl and associates to our knowledge of atomic structure and to the development of new experimental techniques has resulted in many applications of importance to national defense and industry. The applications, at first unpredictable, finally arise as pieces of seemingly remote knowledge become pieced together. Some of these include microwave radar, atomic clocks for timing devices, masers for improved early warning and radio-telescope devices, sensitive magnetometers, and new communications equipment. Further benefits to the Navy continue to accrue in the form of ideas, devices, and systems as a result of association with the frontiers of this field of science. It is now clear why leading research administrators agree that the path to progress in a field of basic research is to back the competent scientist and let him explore for the facts which lead to understanding.

An important corollary benefit of the Navy research program is the training of basic research scientists. It supplements the primary effort of the National Science Foundation in this field in areas of direct interest to the Navy. An interesting example of this is the strengthening of our capabilities in underwater sound. Through basic research contracts with universities it was possible in five years to more than double the number of trained men in this portion of physics so vital in anti-submarine warfare. Many who leave the field of basic research following their training also become of key importance to the Navy. For example, a brief study of the weapons systems program of the Navy indicated that applied research and development in most projects is so complex that the great majority of those chosen to become project leaders are persons whose training was in basic research. They combine the rare ability to understand the broad problems, to plan programs and to make key contributions.

an important corollary benefit of the Navy research program is the training of basic research scientists

Fields of Science Related to the Missions of the Navy

Because of the great diversity of Navy missions, its interests necessarily extend into most of the major fields of science. The following is a list of these fields approximately in order of current Navy basic research expenditures:

Physics
Astronautics and Aeronautical Engineering
Material Sciences
Electronics
Mechanics
Medical Sciences
Biology and Biological Sciences
Oceanography
Chemistry
Geography
Psychology
Operations Research
Meteorology
Astronomy and Astrophysics
Mathematics
Combustion
Earth Physics

This cannot be viewed as a priority list as costs of performing basic research vary with the field of science. Any detailed monitoring of the basic research program of the Navy is a large and continuing task, obviously far beyond the scope of this assignment. Some general impressions gained, however, are considered worth mentioning.

Figure 10

Coupling Between Segments of the Research Process

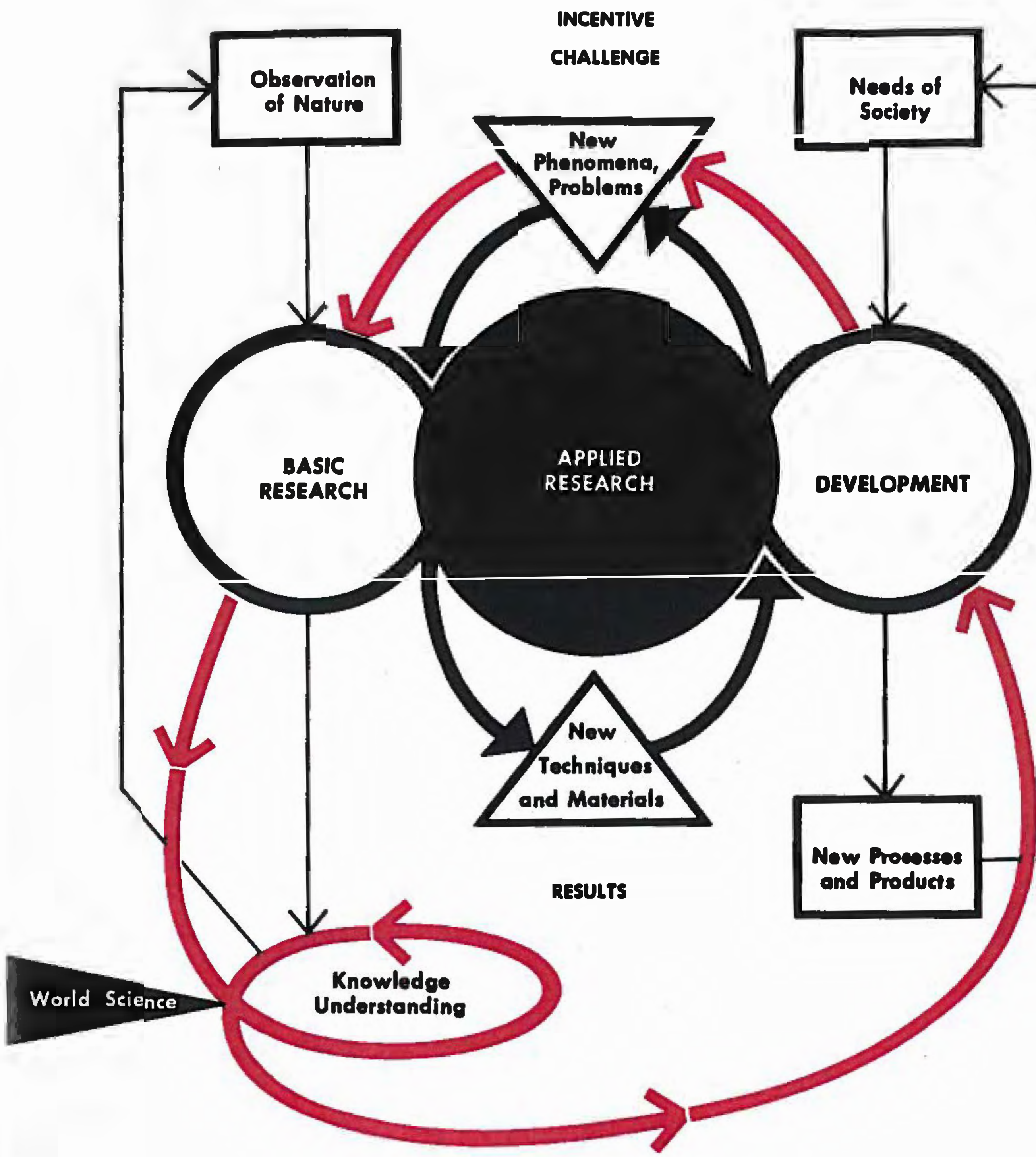
Basic Research Provides the Life Blood

This diagram presents a schematic model of the research process. Inspection shows immediately that the collective use of human intelligence in research involves a system of interconnecting circuits.

A characteristic of each of the three major segments, basic research, applied research, and development, is an ability to feed upon itself as well as upon other segments. Ideas wherever originated within the system continually generated new ideas. This is shown by the several cyclic lines. Perhaps the best proof of this phenomenon of regeneration or feedback is the tremendous growth rate of science. This same feedback principle is easy to visualize in the case of the military program in that each new measure immediately sparks the necessity for development of a countermeasure.

But the strongest characteristic of the research process is the requirement for coupling between the three segments. The key to this coupling is the transmission and use of the knowledge and understanding which springs from basic research. This circulation of new knowledge gained through basic research can be thought of as the life blood of the research process, as indicated by the red line. It is only by establishing such flow to permit easy and understandable communication with the frontiers of science on a world-wide basis that a healthy and progressive research program can be maintained That this can be accomplished by the Navy only by actually participating in basic research, not through dependence on a separate agency, is agreed upon by all leading research administrators. Participation in basic research injects into a program basic scientists in a manner which permits them to tap the important reservoir of world science and to catalyze the progress of the entire effort. This is one key to minimizing the time cycle from new research discovery to production.

A few examples of the benefits already accruing to the Navy by the close coupling of its basic research with applied research and development are shown in brief below the model.



THE MACHINERY OF THE RESEARCH PROCESS

. . . . basic research provides the life blood

Figure 10

The listed fields of science are logically of interest to the Navy. In them the areas of opportunity in assisting the furtherance of the missions of the Navy are legion. Better understanding of such things as the elementary particles, nuclear forces, chemical bonds, mathematical techniques and tools, atmospheric physics, dynamics of oceans, man-machine complexes, solid state, plasma characteristics, and hydro-dynamics offers a multitude of possibilities in new systems of warfare much beyond our ability to predict.

However, the Navy obviously cannot and should not cover all aspects of these fields of science. In its planning the Navy must take what amounts to two cuts in establishing a program. The first cut involves a general allocation of effort between fields, depending on Navy interest, and the extent to which others are already providing support. The second cut gets down to the type of detail wherein the science administrators, working with the advice of competent scientists, must have authority to place their bets on the basis of the competence of the investigator and the relevance of the project. Within each field of science listed there will be three types of project choices. One type will be of direct Navy interest. A second type will be of interest, but less obviously so. A third type will be of only speculative interest, but nevertheless one with which the Navy should be in communication lest a breakthrough of vital importance occur. A classic example of the latter was early Navy work in nuclear physics which ultimately permitted more rapid utilization of nuclear power for ship propulsion. It is not possible to define firm boundaries as to Navy interest because of the unpredictability of basic research results and the complex inter-relationships between fields of science. Thus, trying to look into the future intelligently is the thing which causes every research administrator to lose sleep. This is when wisdom to make the proper choice, patience to await results, and strength to justify expenditures become so important.

While existing Navy program planning, selection of contractors, coordination with other agencies, and communication are generally good, there is always room for improvement. In the planning of research it should be possible to make use of additional scientists and research administrators from universities and industry. In this way more information can be obtained on programs under way in many fields of science, on new basic research policies of others to permit comparison with those of the Navy, and on new techniques of planning and budgeting. This should strengthen the basic research program and project selection, and tend to eliminate any unnecessary overlap with expanding industrial basic research. Improvement in communications should also be possible. In this area the Navy faces a difficult problem, since more than one half of its basic research is, quite properly, performed by contract. This means that a special effort must be made to closely couple this work with the applied research and development programs in Navy contractor and subcontractor laboratories. Improved communications require continued emphasis on personal contact through meetings arranged by science administrators and liaison personnel, and improved means of recording and distributing information in readily accessible form. Adequate travel funds will be a necessity.

the appropriate Navy laboratories are well aware of the importance of basic research

The appropriate Navy laboratories are well aware of the importance of basic research in maximizing their contributions to furthering the missions of the Navy. In this regard they are outstanding among the Department of Defense Laboratories. The Naval Research Laboratory, which compares favorably with many top industrial laboratories in devoting 20-25 percent of its funds to basic research, is responsible for about 30 percent of all papers published by the 49 Department of Defense establishments publishing in 16 selected scientific journals. Other highly rated Navy laboratories such as the Naval Ordnance Laboratory, Naval Ordnance Test Station, and Navy Electronics Laboratory were also found to be publishing significantly. The knowledge generated in the basic research work of these and other Navy laboratories, and knowledge gained through their contacts with basic research performed elsewhere, have contributed significantly to improved Navy effectiveness.

However, in discussions of the Navy program with the top scientists in many of the Navy laboratories, it was evident that they believed the Navy budgetary and administrative policies with respect to basic research were too limiting. Among these men so well aware of the serious problems in national defense today there was general agreement that the Navy should place much greater emphasis on participation in, and communication with, that segment of science responsible for the initiation of our major technological innovations. As will be seen in the next section, there is much justification for their considered position.

An Approach to Establishing A Proper Level of Navy Participation in Basic Research

Two methods of approach were selected in attacking the problem of establishing a proper level of Navy participation in basic research.

The first involved seeking out the judgment of many people competent in research and its administration, and responsible for setting the basic research budgets within their own organizations. The policies and practices of large segments of industry and government were investigated. New data on research and research personnel were collected and analyzed.

The second involved a mathematical analysis of the research process in an attempt to develop a method of predicting for a given project the optimum division of effort to be devoted to basic research, applied research, and development. If this can be done, it should then be possible to project the analysis to cover the Navy broadly.

At the beginning of the study it became painfully evident from the diversity of opinions encountered that the definition of basic research was a matter which had to receive detailed attention. For purposes of this project the official Department of Defense definition, as previously recorded, was adopted. While this definition, as that of any general concept, is necessarily broad, it was found to have rather wide acceptance. The problem, however, lies in the interpretation of the definition. Argument over the meaning of basic research definitions has gone on for some time, as is evident both in reports of Congressional hearings and reports of meetings of research administrators. Unless the definition is interpreted similarly, it would be impossible to obtain comparative data on basic research budgets and policies from Government, industry, and university sources.

It was decided to attack this problem by ignoring the debate over the meaning of definitions, and proceed directly to a study of the output of *cases of secrecy in basic research are infrequent and merely delay, rather than prevent, publication*

basic research. The concept that the output of all meaningful basic research is almost invariably represented by scientific papers published in recognized scientific journals was found to have almost universal acceptance by research personnel and administrators.*

Cases of secrecy in basic research are infrequent and merely delay, rather than prevent, publication. Therefore, it was reasoned that if there is widespread consistency in the interpretation of the definition of basic research, there should be a correlation between the number of people claimed to be performing basic research in Government, industry, and university laboratories, and the number of papers originating from each of these sources appearing in selected scientific journals.

In the exploration of this thought, data previously collected by the National Science Foundation were used to calculate the number of basic research workers claimed in 1953-54 by Government, industry, and university laboratories. The number of papers originating from each source was then obtained from inspection of a selected sample of thirteen recognized scientific journals covering various major fields of science. The publication count was for the year 1957, permitting a reasonable elapse of time for research and publication. The results obtained are recorded in Table I.

The strong correlation shown in Table I permits the conclusion to be drawn that policy with respect to the interpretation of what constitutes basic research, and freedom to publish, is remarkably consistent nationwide. With the growing tendency for more liberal publication policies on the part of industry, there is indication that the correlation will become even stronger.

This gratifying and significant finding had two important results. First, it meant that comparable data on basic research policies and budgets could be obtained from various sources. Second, it permitted a rough check to be made so that the validity of data from a given source might be determined, when desired, merely from a simple literature count. Such checks applied to a number of Government and industrial laboratories further confirmed the conclusions drawn from Table I.

Comparison of Navy and Industry Basic Research Allocations

industry represents the second largest source of basic research funds

Industry represents the second largest source of basic research funds in the United States. Since many corporations each year face budget problems of a complexity, if not magnitude, comparable with the Navy, it was decided to compare the practices of the two with respect to basic

* Assistance on this subject from Dr. John C. Fisher of the General Electric Co. is gratefully acknowledged.

research. Inquiries were directed to a large segment of our more technically based industry. Cooperation was excellent. Through discussion and correspondence information was obtained from thirty-three leading corporations representing the source of almost one fifth of the nation's and one half of industry's total basic research funds. Information on the Navy was obtained through the Office of Naval Research.

TABLE I

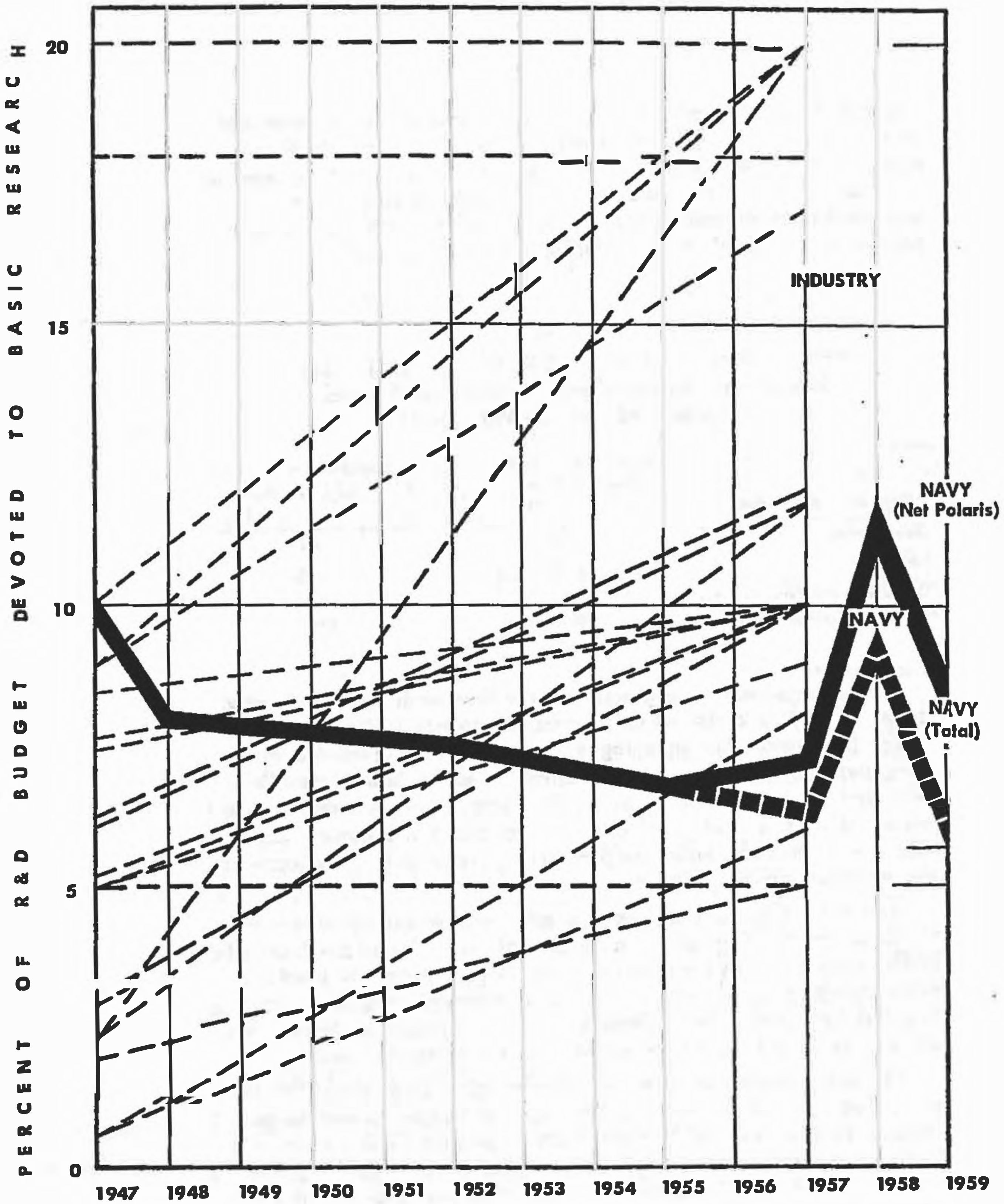
Relation Between Number of Basic Research Workers Claimed and Output of Basic Research as Measured by Scientific Papers Published

Type of Organization	Distribution of Basic Research Workers, 1953-1954	Distribution of Papers Published in 13 Selected Scientific Journals, 1957
Government	7%	9%
Industry	27%	19%
University and Non-Profit Institutions	66%	72%

For a comparison of the practices of the Navy with those of industry, it was decided to study the trends over the decade 1947 to 1957. The earlier date marked the beginning of major Navy basic research expenditures, and 1957 represented the last full year for which data were available from industry at the time of this undertaking. Data were collected in terms of dollars, or, where such data were confidential, in terms of allocation of funds. By this is meant the percent of the research and development budget devoted to basic research.

The industry information was obtained from those executives responsible for allocation of funds within the over-all research and development budget as approved by the Board of Directors. The funds considered were solely corporate funds, exclusive of any Government research contracts. Engineering expenditures of a type not normally included in the research and development budget were excluded from the data obtained.

The data obtained are extremely interesting. A graph presenting the percent of the total research and development budget devoted to basic research in 1947 and 1957 by the Navy Department and by nineteen leading corporations is shown in Figure 11. From this it is readily apparent that, while the Navy compared very favorably with industry in 1947, when it devoted 10 percent of its research and development budget to basic research, industry has since outstripped the Navy in emphasis on basic research. This has come about largely as a result of the growing realization by industrial management of the importance of participating in, and communicating with, that portion of science which creates the



PROPORTION OF RESEARCH AND DEVELOPMENT DEVOTED TO BASIC RESEARCH

. . . *a comparison between the navy and twenty leading industrial corporations*

Figure 11

knowledge and understanding from which burst forth our major technological advances. Put in another way, applied research and development tend to proceed more rapidly, and at lower cost, when adequately backed by basic research.

applied research and development tend to proceed more rapidly, and at lower cost, when adequately backed by basic research

That the Navy operates today in a fiercely competitive field having a high technological obsolescence rate, is generally agreed upon. Some 80-100 percent of ships, aircraft and missiles scheduled for purchase in 1959 were of types not in existence in 1955. Thus, for more meaningful basic research guidelines, the Navy should be compared with corporations in high technological obsolescence rate industries. Two of the most successful corporations in five such industries (chemical, petroleum, communications-electronic, pharmaceutical and materials) were selected for study. These ten corporations had a minimum of 10 percent and a maximum of 20 percent of their research and development budget allocated to basic research. The average was about 16 percent, or more than double the present Navy figures of 6-8 percent.

Other figures confirm the faster pace of industry. Fourteen top corporations in these same industries released to us dollar figures in order to permit comparisons with the Navy. Between 1947 and 1957 these corporations tripled their research and development expenditures and increased basic research expenditures by a factor of 4.5. In the same period the Navy doubled its research and development expenditures, but increased basic research expenditures by a factor of only 1.5. This smaller increase in basic research expenditures by the Navy was essentially offset by reason of the fact that total cost per scientist increased about 50 percent during this same period. This figure of a 50 percent increase has been the experience of a number of laboratories, and is more meaningful than the lesser increase in Consumer Price Index, which has been used in some comparisons.

But the Navy cannot be directly compared with any one corporation or group of corporations. Missions, competitive situation, size, and complexity are all different. Nowhere is success more important today than in military technological advance. The consequences of being second best in national defense today represents a risk far greater than faced by any corporation. Recognizing this, we requested a number of leading research directors to project their experience and judgment into consideration of the problem of Navy participation in basic research. Thirty-three were approached, all representing corporations considered to be outstanding in their particular fields. Of these, sixteen believed they had sufficient knowledge of the Navy to be willing to express an opinion. They were unanimous in their belief that the Navy should increase its participation in basic research. The majority thought that the complex nature of the mission of the Navy was such as to command an allocation of some 15-20 percent of the research and development budget to basic research. This represents a substantial increase over the current Navy allocation of 6-8 percent.

the consequences of being second best in national defense today represents a risk far greater than faced by any corporation *research cannot be turned off and on without producing disruptive effects on program and organization*

Although numerical ratios are often cited as measures of desirable levels of research and development effort, it must be understood that these are to be taken as general guidelines and not as "magic numbers" or rigid criteria. While ratios of 1-5 percent of the sales dollar devoted to technical work are generally quoted, no company, we believe, establishes an over-all figure for its research and development budget on such a basis. Actually the practice is to evaluate the need for technical effort on recommended projects or areas according to the desired rate of progress, and then to total project requirements as a preliminary over-all budget. This is reviewed with top management, and any readjustments made by changing emphasis on individual projects. Admittedly there is usually a historical trend in the budget which might make it appear that somewhat fixed ratios are used. The hazard of the fixed ratio is that it might cause fluctuations inimical to sound research planning. Research cannot be turned on and off without producing disruptive effects on program and organization.

If one considers specifically the information obtained from industry regarding the percentage of total research and development budget devoted to basic research, it should be noted that these percentages were not set arbitrarily at fixed levels, but have been reached over the years on the basis of judgment as to optimum balance between the need for new knowledge and the effort required to apply the accumulation of knowledge to the company's business.

The level of basic research effort suggested as appropriate to the needs of the Navy is, therefore, to be taken as a general guideline. It is implicit that the budget be erected on the basis of careful evaluation of the need for new knowledge, area by area, and that as increased effort appears to be justified, the total of the sub-budgets would be gradually increased in this step-wise fashion.

One of the concepts most often encountered when research policy was discussed with industry was that one should never do less basic research than his strongest competitor. With this in mind, it is desirable to assess briefly the Soviet situation, since the Navy must play its part in meeting this challenge. The best estimates which could be made within the scope of this report indicate the following:

> Soviet political leaders are credited by a number of investigators with a greater knowledge of science than ours, and a greater appreciation of its role in furthering the progress of a nation. This disparity is not confined to Government circles; indeed, the percentage of ministerial-rank persons having a scientific or technical education is higher than that found at the management level of most top corporations in the United States. In fact, the USSR appears to be the first nation to fully appreciate the importance of science. This is evident in many areas such as the vast effort in technical education, the high percentage of gross national product expended on research and development, the important stature accorded scientists in the Soviet society, and the large program to collect, translate, and disseminate scientific publications.
>
> The current policy of the Soviet Government appears to be to direct the development of its science and technology toward achieving military, political, and economic supremacy over the United States. Back of the recent technological successes by the Soviet is a program of basic research staffed by approximately the same number of scientists as that of the United States. Whenever such a situation occurs the nation which places more emphasis on a particular field of science will tend to lead in that field. While over-all comparisons have many shortcomings, it appears that currently the United States leads the USSR in most areas of physics, mathematics, medicine, and chemistry; is on a par in aviation and space medicine, metallurgy, combustion, theoretical physics, meteorology, and oceanography; and is behind in physical chemistry and many areas of geophysics.
>
> The important problem, however, is the future. Currently the Soviet is training persons capable of performing basic research in science at a rate approximately 50 percent greater than the United States, while essentially keeping abreast of the United States in granting doctorate degrees in other fields. Thus, the Soviet potential is increasing relative to ours at an alarming rate.

This brief account of the competition presents a real challenge to the nation. The outlook is not entirely black. But to meet the challenge will require increased wisdom both in the planning and administration of research and development to make most effective use of our resources, and in the training of additional men of higher quality.

Some of the Problems of Increasing Navy Basic Research

Should the Navy decide to increase its participation in basic research, at least two problems will arise. One will be availability of scientific manpower, and the second will be improved methods of budgeting. Therefore, consideration was given to these matters.

At present it appears possible to increase the basic research participation of the Navy. This opinion is based on the outcome of a study by the Coordinating Committee on Science of the Department of Defense. It showed that for 1957, if funds had permitted acceptance of all meritorious proposals, the Department of Defense basic research effort in outside contracts could have been increased 70 per cent. This figure is probably reasonably accurate, because the increase in proposal submissions which would occur with increased availability of funds would essentially offset the tendency for certain research organizations to suddenly become understaffed through acceptance of all outstanding proposals. The factor of large capital equipment items, which could have a substantial effect on budget and personnel, has been omitted from this particular listing of meritorious proposals. (It is understood that this is the subject of a separate study.) In addition, a rough approximation indicates that an increase in basic research effort of about 10 percent could be made now in Navy laboratories. The situation of having additional personnel currently available will not persist long, because research and development activities are expanding about 10 percent per year, whereas the number of scientists is increasing at a rate of only 5 percent per year.

An interesting approach was made to the study of basic research manpower, involving once again the counting of papers appearing in selected scientific journals. This technique permits two important findings not well covered in previous manpower studies. First, it shows who is performing basic research. One rather disturbing discovery is that only 20-30 percent of all physicists and chemists who obtain doctor's degrees publish basic research papers following thesis submission. It is not known as yet whether this is caused by attraction to other positions having more appeal or reward, or by a lack of ability or interest in basic research. Second, paper counting, although obviously not the whole story, provides a rough means of evaluating basic research scientists. For example, physicists are rated by physicists and other scientists by election to the National Academy of Sciences, as a Fellow of the Physical Society, or as a member of the Physical Society. Study of the records of all physicists earning doctors degrees in 1936, 1941, 1946, and 1951 indicated that Fellows of the Physical Society publish at a rate about ten times that of non-Fellows, and members of the National Academy of Sciences at about twice the rate of Fellows of the Physical Society.

more men will have to be trained, and perhaps more motivated to remain in basic research

It is obvious that if the Navy, other parts of Government, industry, and universities are to increase basic research in any substantial way in the future, more men will have to be trained, and perhaps more motivated to remain in basic research. The latter is not a simple decision, as it has previously been shown that basic research trained men are extremely useful in other occupations. Another method of extending the work of basic research scientists is to provide them with better equipment and more technical assistants. Experience gained in the past six years makes

this appear to be a promising avenue. Whether to try to motivate more persons interested in post graduate work to shift into the sciences is a point of debate. There has been no change in the ratio of science doctorates to other doctorates granted since 1932. Many people believe no effort should be made to upset this relationship, which stands today at roughly 30 percent physical sciences, 20 percent life sciences, and 50 percent doctorates in other fields.

A final problem on manpower has to do with hiring and retaining top flight personnel for Navy laboratories. Since basic research requires excellent personnel, Navy laboratories, to be effective, must be permitted to operate with more competitive salary and administrative policies.

The matter of budgeting for basic research is complicated by the necessity for planning on a long-term basis, while budgeting and operating on an annual basis. Planning basic research involves estimating the time needed to form the research team, perform experiments, and analyze and publish the results. The over-all time required for this process, as measured by the current average life of Office of Naval Research projects, is 5.1 years. This figure varies with the size of the project, those of less than $10,000 averaging 3.5 years, those of $10,000-$30,000 per year averaging 4.8 years, and those greater than $30,000 per year averaging 6.5 years. The Office of Naval Research has been able to obtain the budgetary mechanisms for long-term financing of basic research. Its funds are made available by means of a no-year (available until expended) appropriation, which helps solve most if not all of the legal and contracting problems involved in long-term financing. In addition, it has Congressional approval of the policy of long term advance financing of research projects. Under this policy projects are financed for an average of two years with individual contracts funded as far in advance as five years. The use of these budgetary tools is, however, strictly limited by the amount of funds made available each year and by the uncertainty of subsequent years' appropriated amounts. Stiff competition for funds is offered by current fleet readiness, hardware, and personnel requirements.

The budget problem is one of broad national interest, involving many agencies in addition to the Navy Department. The solution can be obtained by providing better understanding of the role of basic research to serve as a basis for coordinated budget planning by the Executive Branch and Congress. Since the Office of Naval Research has had so much experience with this problem, it could serve as an excellent testing ground for improved procedures.

A Proposed Mathematical Model of the Research Process

The invention of a new device or process is essentially a synthesis, a putting together of principles, relationships, and facts. These building blocks of invention themselves all had to be discovered. Many of them were discovered so long ago that they are now taken for granted, such things as the wheel and the screw, such materials as iron and glass. Others are more recent, but new enough so that we realize that they have not always been available, for example the electric motor. Still others are so new that the public is not generally aware of them.

No matter how many or how few these principles, relationships, and facts may be, one thing is certain: the invention could not have been made until all were discovered. There is therefore an earliest date at which any invention could have been made. No matter how great his genius, Leonardo da Vinci could not have invented television. This is not to say that inventions cannot be conceived before their time. Jules Verne conceived a missile fired around the moon, but in his day the actual construction and firing of such a missile was quite impossible.

in every invention there exists a key fact

In every invention there exists a key fact, the last to be discovered of all the facts, relationships, and principles which were necessary before the invention could be made. The date of the discovery of this key fact is the earliest date at which the invention could have been made. Some inventions have been made very quickly after the discovery of the key fact, others have been made long after, but no invention was ever made before the discovery of its key fact.

Research is the process by which these principles, relationships, and facts are discovered. Without research, invention must come to a stop, for there is a finite number of ways in which a given body of knowledge can be applied. This is not to say that the stoppage would be instantaneous, for it takes time for inventions to be made, but without research the rate of invention would grow slower and slower until it fell to zero.

This decay in the invention rate may be thought of in the following way. At any instant of time there exists a body of knowledge, a set of facts, etc., which have been discovered. Some of these may be useless, and will never play any part in any invention. Some may be applied once, others many times. Among these a few are key facts, the discovery of which makes an invention possible.

The number of facts required for an invention is ordinarily very large, but only one is the key fact. While a certain fact may be used in a large number of inventions, it is most probable that it is not the key fact in any of these. There is some chance that it may be the key fact in one invention, but, as a matter of experience, very unlikely indeed that it is the key fact in more than one.

Coming back to our body of knowledge, this body contains a certain number of key facts, corresponding to an essentially equal number of possible inventions. If no new knowledge is added by research, these represent all the inventions which can be made.

We can symbolize this process by comparing it to a two stage chemical reaction

$$A \longrightarrow B \longrightarrow C^{*}$$

Where A represents the key facts not yet discovered, B represents the key facts which have been discovered, but not yet applied, and C represents the final applications. The first step is the research process of finding the key facts. The second step is the process of invention.

The chemical analogy suggests, and the theory of search developed during World War II reinforces, the idea that the rate of the first step is proportional to the effort put into the process and to the number of undiscovered facts. Similarly, the rate of the second step should be proportional to the effort put into it, and to the number of discovered, but unapplied, facts. Thus the first rate should be of the form

$$k_1E_1A$$

and the second of the form

$$k_2E_2B$$

where E_1 and E_2 are the respective efforts, and k_1 and k_2 are the two constants of proportionality.

The constants k_1 and k_2 are measures of the relative ease with which the two processes can be carried out. If k_1 and k_2 are equal, the two processes are equally easy. If $k_1 = 10\, k_2$, it is 10 times as easy to find a fact as to apply it, and so on.

To find the proper balance of effort between the two steps, it is clearly necessary to find a way of determining these "ease factors." One approach to this is by the analysis of past experience. Let us suppose that during the development of a field the effort put into each of these two processes is held at a constant ratio. It can then be shown that the number of facts in the three categories A, B, and C should change with time in the way shown in Figure 12.

If it were possible to observe all three of these curves the analysis would be relatively simple. Unfortunately data of this kind are hard to obtain. The only data we have been able to find are a few cases, which give only the C curve. These few cases, however, are in excellent agreement with the prediction of this theory. Furthermore, they indicate a ratio of k_1/k_2 in the neighborhood of 2. That is to say, it is twice as easy to discover a fact as to apply it.

It would be risky in the extreme to draw the conclusion that this ratio is universal. It may very well be that this ratio varies widely from one field of research to another. Nevertheless the data do suggest that the

* Detailed development of the mathematical model is given in Volume II.

general lines of the theory may be correct, and that the "ease factors" are at least of the same order of magnitude.

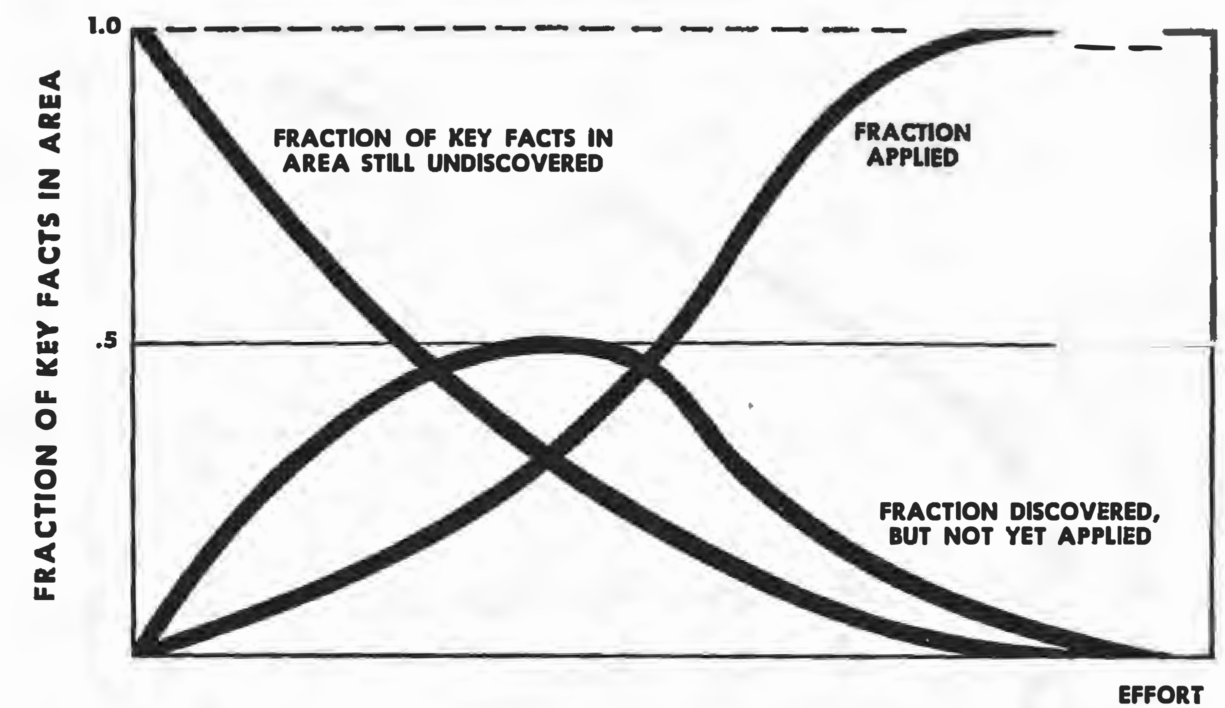
If this theory of the research process can be accepted, it now becomes possible to study the problem of the correct distribution of effort between the two steps. It is clear that both kinds of effort are necessary; the question is: how should a given total effort be divided?

If too much effort is put into the first step, and too little into the second, the result will be the discovery of a large fraction of the key facts, but the application of only a small fraction of those discovered. If too much effort is put into the second step, and too little into the first, only a small fraction of the key facts will be found. While a large fraction of the discovered facts will be applied, the number of applications will be small because the number of discovered facts is small.

The general situation is shown in Figure 13. The three curves in this figure represent three levels for the total amount of research effort put into the development of a field. Each curve shows how the total result of the effort (measured as the number of inventions) changes as the distribution of the effort between basic research (step 1) and applied research and development (step 2) is varied. If the total effort is small, the best result is obtained when the two efforts are equal. As the total effort is increased, the position of the maximum shifts. How this shift takes place depends on the "ease factors," k_1 and k_2. The curves in Figure 13 are drawn for a case in which k_1 is larger than k_2. In this case the shift is toward less basic research and more applied research. If k_2 were greater than k_1, the shift would be in the opposite direction.

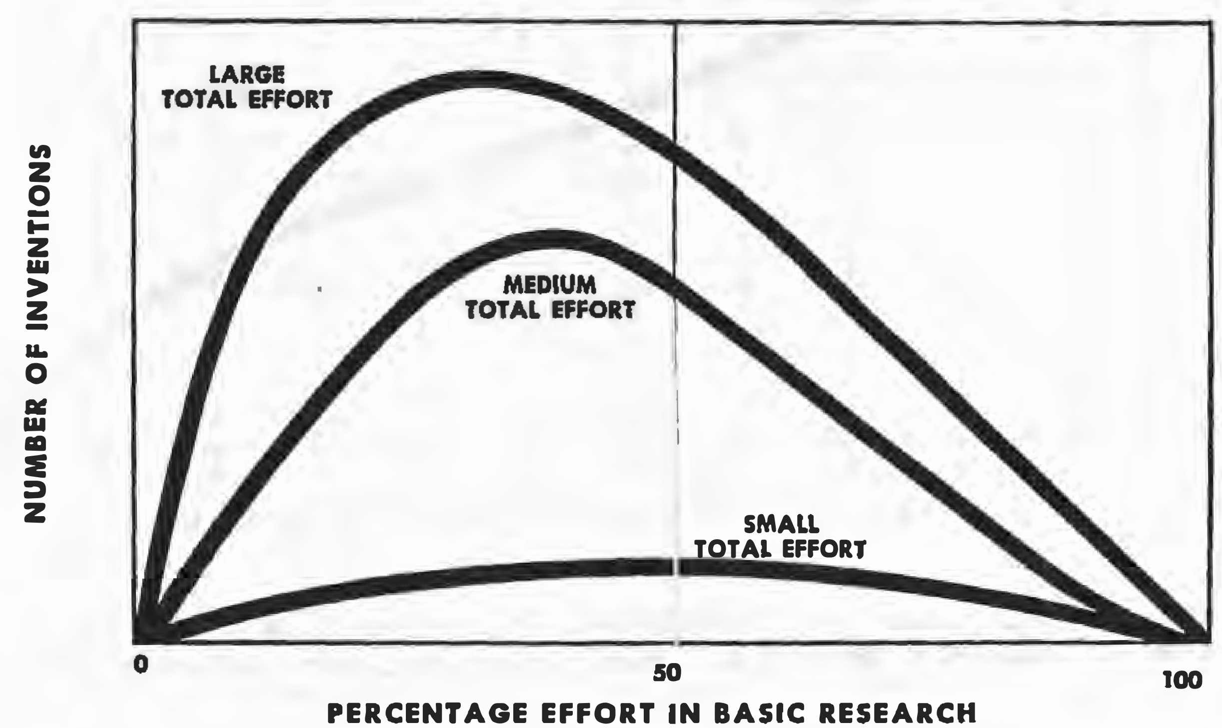
Figure 14 shows these shifts in greater detail. The curves show the way in which the optimum distribution of effort changes as the total effort is increased. The curves are plotted for the three cases $k_2 = 9\,k_1$, $k_1 = k_2$, and $k_1 = 9\,k_2$. Taking the curve $k_1 = 9\,k_2$ as an example, the curve shows again that for small efforts, the effort should be equally divided between basic and applied research. As the total effort is increased, the fraction which should be devoted to basic research decreases. It should be noted that the horizontal scale in this figure is the fraction of the possible inventions which are made. The right hand side of the figure therefore represents an infinitely large effort.

If the present indications are to be believed, the actual ratio of k_1 to k_2 is about 2. If this is the case, the optimum fraction of basic research in a large program to develop a field should be in the neighborhood of 30%. This suggests that a larger effort should be placed in basic research than is now the case. We hope that in the future additional data will become available so that this indication can be tested further.



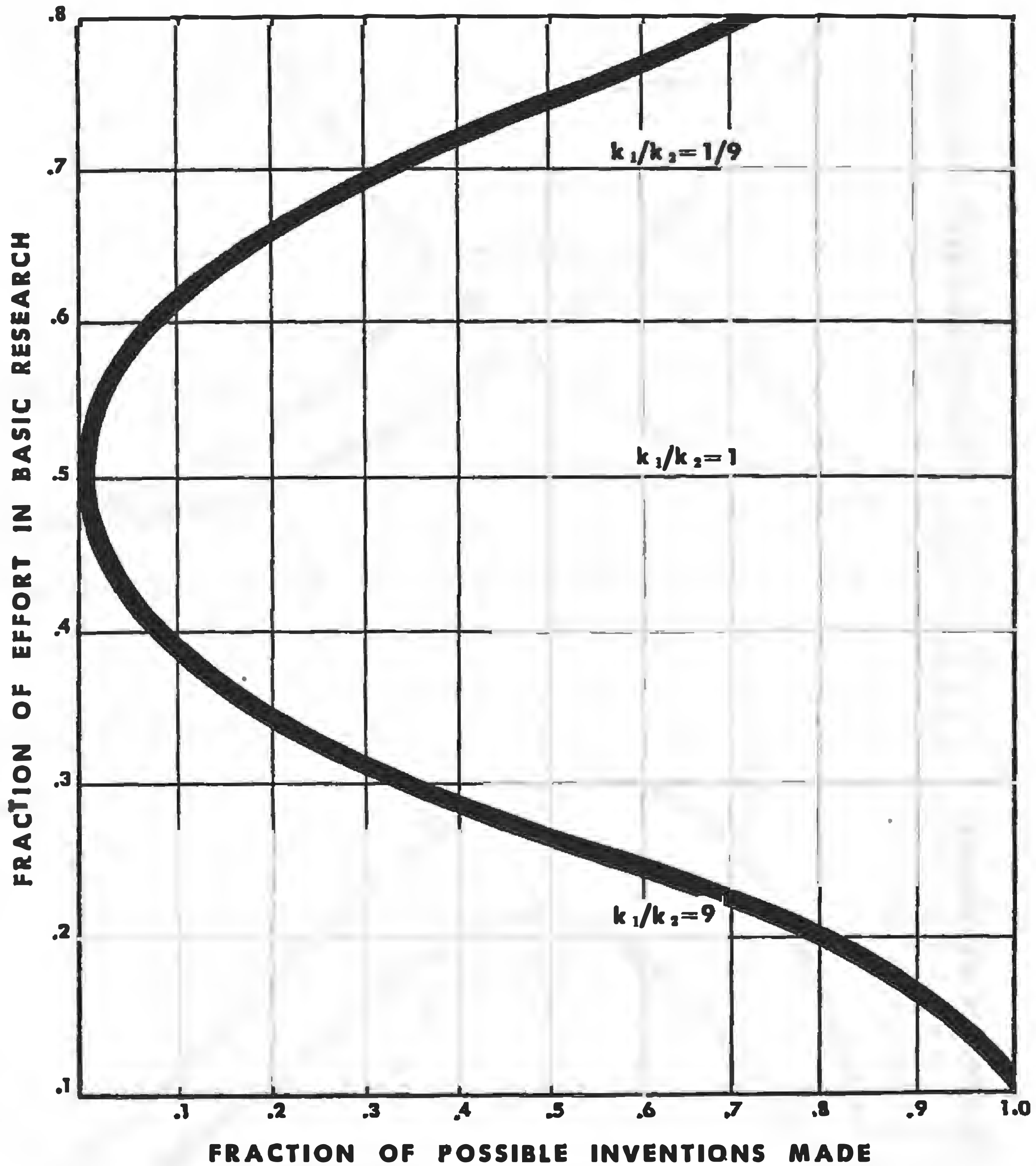
A TYPICAL HISTORY OF THE RESEARCH PROCESS

Figure 12



DEPENDENCE OF RESEARCH RESULTS ON DISTRIBUTION OF EFFORT

Figure 13



FRACTION OF EFFORT IN BASIC RESEARCH AS A FUNCTION OF THE DEGREE OF CONVERSION OF FACTS TO INVENTIONS

Figure 14

Acknowledgments

It is a distinct pleasure to be able to state that assistance in the preparation of this report has been willingly supplied by a great many individuals associated with Government, universities, and industry who were consulted during the course of the study. To list all to whom we are indebted would literally require several pages.

In particular we would like to acknowledge the assistance of the Office of Naval Research, U. S. Naval Training Device Center, R. C. Cowen, and the following individuals associated with this study through the Naval Research Advisory Committee: L. A. Cookman, W. H. Doherty, M. J. Kelly, A. B. Kinzel, R. W. Larson, L. McKenzie, G. M. Morrow, E. R. Piore, and C. G. Suits, Chairman.

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Volume II

A REPORT TO THE

Secretary of the Navy

ON

Basic Research in the Navy

BY THE

Naval Research Advisory Committee

June 1, 1959

Report Prepared
by

Arthur D. Little, Inc.

UNDER OFFICE OF NAVAL RESEARCH CONTRACT NO. NONR-2516(00)

Introduction

Upon the recommendation of the Naval Research Advisory Committee, the Office of Naval Research initiated a contract with Arthur D. Little, Inc., February 1, 1958, to perform a study to determine a basis for decision as to the proper level of support of basic research by the Navy Department.

The report of this study is in two parts. Volume I is a brief monograph setting forth the principal findings. This is under separate cover. Volume II is a series of memoranda covering studies undertaken during the assignment, which led up to the principal findings. These are submitted herewith in the following appendixes:

A. Method of Approach

B. Mathematical Model

C. Manpower Studies

D. Chronology of Naval Technical Developments

E. References and Source Material

Appendix A

Method of Approach

The study was carried out by a team of people organized especially for the project under the over-all direction of a project leader. The team consisted of essentially three groups:

Executives experienced in research and its administration and familiar with Government research policies and organization.

Scientists experienced in basic research.

Operations research personnel experienced in mathematical analysis and data handling.

Excellent liaison was established with the Navy through the Office of Naval Research and a special subcommittee of the Naval Research Advisory Committee.

the team was split into two major groups

Following the outline of a method of attack, the team was split into two major groups. One group was to collect information on basic research practices, policies, and personnel from Government, industry, and university sources; and analyze the data as to its application to the establishment of Navy policies. The second group was to attempt to develop quantitative methods of determining a proper level of Navy participation in basic research.

An extensive series of visits and interviews were arranged, and considerable correspondence with outstanding people in the field was undertaken. Among the groups or agencies contacted were:

Science Advisory Committee to the President, Office of Secretary of the Navy, Office of Naval Research, Office of Chief of Naval Operations, various Bureaus and Offices of the Navy Department dealing with research, a number of Navy laboratories, and the top technical people in nearly all the laboratories, Office of Assistant Secretary of Defense for Research and Engineering, National Science Foundation, Interdepartmental Committee on Scientific Research and Development, Central Intelligence Agency, Bureau of the Budget, and Armed Services Technical Information Agency.

Appendix B

A Model For The Discovery and Application of Knowledge

James C. Hetrick & George E. Kimball

It has been observed historically that the development of a field proceeds as a step function, with a "breakthrough" opening a new body of knowledge which is then explored and applied. Within the region of a single "step", the development follows the familiar S-shaped "growth" or "logistic" curve, as has been independently noted by several observers. An attempt is made here to derive a mathematical model which agrees with this observation and gives some insight into the necessary relationships among the several types of investigative effort.

To construct the model, let us initially postulate a logical universe defining a field of knowledge which can be expressed by a finite number of categorical statements. Within this universe, we characterize knowledge as being in three classes:

within this universe we characterize knowledge as being in three classes

A, the body of unknown fact,

B, the body of known, but unapplied fact, and

C, the body of applied fact.

We now assume that at a given level of effort, the rate of transition from A to B, or discovery, is proportional to A, and the rate of transition from B to C, or application, is proportional to B. This assumption leads to the familiar system

$$A \xrightarrow{k_1} B \xrightarrow{k_2} C$$

of chemical kinetics. Here, k_1 and k_2, having the dimensions of reciprocal time, express the fraction of the class converted per unit time and so measure the difficulty of discovery or application in the field. The formulation and solution of this system is as follows.

$$A \xrightarrow{k_1} B \xrightarrow{k_2} C$$

$$\frac{dA}{dt} = -k_1 A$$

$$\frac{dB}{dt} = k_1 A - k_2 B \qquad \left.\begin{array}{r} A = 1 \\ B = C = 0 \end{array}\right\} \text{at } t = 0$$

$$\frac{dC}{dt} = k_2 B$$

For the intermediate, B

$$B = a_1 e^{b_1 t} + a_2 e^{b_2 t}$$

$$a_1 = -a_2 = k_1/(k_2 - k_1)$$

$$b_1 = -k_1 \qquad b_2 = -k_2$$

For the final stage, C

$$C = a_0 + a_3 e^{b_3 t} + a_4 e^{b_4 t}$$

$$a_0 = 1 \qquad a_3 = k_2/(k_1 - k_2) \qquad a_4 = k_1/(k_2 - k_1)$$

$$b_3 = -k_1 \qquad b_4 = -k_2$$

This solution gives a set of curves for A, B, and C as shown in Figure B-1, where the C curve corresponds to that empirically observed.

This simple formulation suffers from a defect in that it presents an unbelievable picture of the "B" state. Literally, it implies that the unit of knowledge once applied, cannot be re-applied in another context — an observation which is at variance with experience. We can explain this quite simply by saying that facts are not applied in units, but in combination. That is, the "k_2 process" yielding to application of knowledge, does not in general apply to a unit of knowledge, but to a conclusion drawn from a number of units of knowledge. Thus a fact may be applied many times, in different combinations with other facts. This however, leads to two difficulties in the simple kinetic model:

a fact may be applied many times, in different combination with other facts

1. The number of combinations available from a number of facts increases extremely rapidly as the number of facts increase, so that neither the B nor C curves will approach a limit, much less decrease.

2. In the event of assuming combinations of "A" state units being themselves "B" state units, the dimensionality of the equation for $\frac{dB}{dt}$ is erroneous.

To remove these objections, we postulate a model based on the following:

1. The results of the reasoning process can be expressed in sorites, or continued syllogisms.

2. The hypothetical and disjunctive syllogisms can be formally translated into categorical syllogisms.

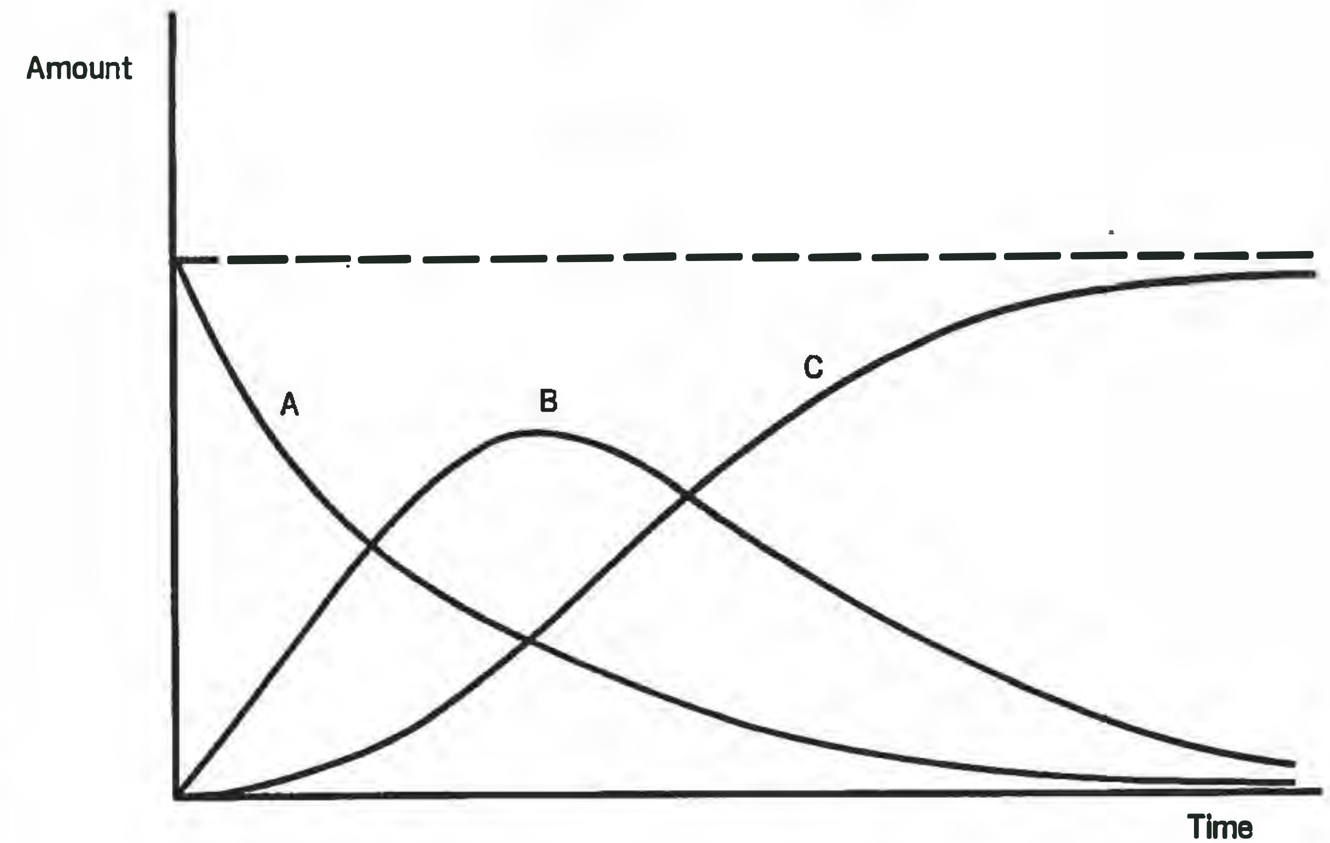


FIGURE B-1

3. All twenty-four valid categorical syllogisms may be reduced to Boolean algebraic formulations amenable to treatment by two theorems of the class-algebra, equivalent to the classical forms Barbara and Darii.

4. The two theorems are equivalent to the application of two relationships, a total inclusion relationship having the full properties of an algebraic inequality and a relationship of partial inclusion having only the property of transitivity over full inclusions, and under certain conditions.

a representation of the universe of knowledge

Under this postulation, the universe of knowledge may be represented as, for example

$$a_1 < a_2 < a_3 < \cdots\cdot < a_n < a_{n+1}$$

where the universe involves $(n + 1)$ classes, related by (n) categorical statements. It is evident, however, that only those statements which are adjacent in the ordered chain are combinatorially meaningful. Thus the statements $a_1 < a_2$ and $a_2 < a_3$ are combinatorially meaningful, and permit the combination (or "application") $a_1 < a_3$; while the statements $a_1 < a_2$ and $a_3 < a_4$ permit no valid conclusion, and hence cannot be applied. If this is so, then for a universe of n relationships, of which m are known, we have the following argument, for an application of such complexity as to require h facts.

The number of ways in which h may be drawn from n is

$$\frac{n(n-1)(n-2)\cdots(n-h+1)}{h!}$$

but the number of meaningful ways in which h facts may be drawn from a set of n ordered as shown is

$$(n-h+1)$$

Thus the probability of a given group of h facts permitting the drawing of a valid conclusion, i.e., an application, is

$$\frac{h!}{n(n-1)(n-2)\cdots\cdot(n-h+2)}$$

But the number of ways in which h facts may be drawn from m is

$$\frac{m(m-1)(m-2)\cdots\cdot(m-h+1)}{h!}$$

Thus the expected number of possible applications of complexity h is the product of these two expressions

$$\left(\frac{m}{n}\right)\left(\frac{m-1}{n-1}\right)\left(\frac{m-2}{n-2}\right)\cdots\left(\frac{m-h+2}{n-h+2}\right)(m-h+1)$$

The total number of applications possible is

$$\sum_{h=2}^{h}\left(\frac{m}{n}\right)\left(\frac{m-1}{n-1}\right)\cdots\left(\frac{m-h+2}{n-h+2}\right)(m-h+1)$$

If now we assume that h is small compared to m and n, i.e., any application draws on only a fraction of known fact this becomes

$$m\sum_{j=1}^{h-1}\left(\frac{m}{n}\right)^{j}$$

If this is taken as an infinite series (which will actually violate the approximation introduced above) the expression reduces to

$$\frac{m\left(\frac{m}{n}\right)}{1-\left(\frac{m}{n}\right)}=\frac{m^2}{n-m}$$

In terms of the postulated two-stage process,

$$m = A_o - A,\ n = A_o \text{ and}$$

$$B + C = \frac{m^2}{n-m} = \frac{(A_o - A)^2}{A}$$

so that the system becomes

$$\frac{dA}{dt} = -k_1 A$$

$$\frac{dC}{dt} = k_2 B$$

$$B + C = \frac{(A_o - A)^2}{A}$$

to which the solution is

$$A = A_o e^{-k_1 t}$$

$$B = k_1 A_o\left[\frac{e^{k_1 t}}{k_1 + k_2} + \frac{e^{-k_1 t}}{k_1 - k_2} + \frac{2k_1 e^{-k_2 t}}{k_2^2 - k_1^2}\right]$$

$$C = k_1 k_2 A_o\left[\frac{e^{k_1 t}}{k_1(k_1 + k_2)} - \frac{e^{-k_1 t}}{k_1(k_1 - k_2)} + \frac{2k_1 e^{-k_2 t}}{k_2(k_1^2 - k_2^2)}\right]$$

In these equations, the term $e^{k_1 t}$ increases without limit, because of the assumption an infinite series implies $j \to \infty$. If an appropriate limit is imposed on the term to satisfy the assumptions that $h << m < n << \infty$, the expression is seen to be of the form required in the kinetic model.

The development can, alternatively, be carried through use of the proper conversion of the expression

$$m\sum_{j=1}^{h-1}\left(\frac{m}{n}\right)^{j}$$

as a geometric series of $(h - 2)$ terms. This is equal to

$$m \cdot \frac{m}{n} \cdot \left[1 - \left(\frac{m}{n}\right)^{h-1}\right] \Big/ \left[1 - \left(\frac{m}{n}\right)\right] = \frac{m^2}{n-m}\left[1 - \left(\frac{m}{n}\right)^{h-1}\right]$$

where again $n = A_o$; $m = A_o - A$.and hence

$$B + C = \frac{m^2}{n - m}\left[1 - \frac{m^{h-1}}{n}\right]$$

$$= \frac{(A_o - A)^2}{A}\left[1 - \left(\frac{A_o - A}{A_o}\right)^{h-1}\right]$$

The resulting series of equations are best solved numerically, rather than analytically. When this is done, again curves of the proper shape are obtained.

more complicated cases give similar, but more elaborate equations

More complicated cases, such as those in which branching is introduced into the chain of relationships between classes, give similar but more elaborate equations which again on numerical solution give curves of the proper form. Accordingly, it is assumed that the basic form of the C curve as being a constant minus two exponentials.

Let us now consider such an expression, containing two exponentials and possibly a constant. Thus in the first formulation for B we have

$$B = a_1 e^{b_1 t} + a_2 e^{b_2 t}$$

Now consider three successive points taken for equally spaced values of t

$$B_i = a_1 e^{b_1 t_i} + a_2 e^{b_2 t_i} \quad (1)$$

$$B_{i+1} = a_1 e^{b_1 t_i} e^{b_1 \Delta t} + a_2 e^{b_2 t_i} e^{b_2 \Delta t} \quad (2)$$

$$B_{i+2} = a_1 e^{b_1 t_i} e^{b_1 2\Delta t} + a_2 e^{b_2 t_i} e^{b_2 2\Delta t} \quad (3)$$

If now we multiply (1) by $e^{b_1 \Delta t}$ and subtract from (2), and multiply (2) by $e^{b_1 \Delta t}$ and subtract from (3), we have

$$B_{i+1} - e^{b_1 \Delta t} B_i = a_2 e^{b_2 t_i}(e^{b_2 \Delta t} - e^{b_1 \Delta t}) \quad (4)$$

$$B_{i+2} - e^{b_1 \Delta t} B_{i+1} = a_2 e^{b_2 t_i}(e^{b_2 2\Delta t} - e^{(b_1 + b_2)\Delta t}) \quad (5)$$

Now, multiplying (4) by $e^{b_2 \Delta t}$ and subtracting from (5), there results

$$B_{i+2} - (e^{b_1 \Delta t} + e^{b_2 \Delta t}) B_{i+1} + e^{(b_1 + b_2)\Delta t} B_i = 0 \quad (6)$$

From which

$$\frac{B_{i+2}}{B_i} = \left(e^{b_1 \Delta t} + e^{b_2 \Delta t}\right) \frac{B_{i+1}}{B_i} - e^{(b_1 + b_2)\Delta t} \quad (7)$$

Thus if the indicated ratios are plotted, the points should fall on a straight line of slope m and intercept b such that the roots of the quadratic

$$x^2 - mx + b = 0$$

are $e^{b_1 \Delta t}$ and $e^{b_2 \Delta t}$. A similar expression results if C alone is known as a function of t, except that the successive increments ΔC at equal Δt are used. To illustrate this, synthetic data for the intermediate, B, in a system with $k_1 = 0.10$ and $k_2 = 0.05$ are plotted in Figure B-2. The accompanying curve, Figure B-3, for $\Delta t = 5$ is the straight line

$$\frac{B_{i+2}}{B_i} = 1.385 \frac{B_{i+1}}{B_i} - 0.4724$$

which gives values $k_1 = 0.0988$ and $k_2 = .0508$. The following Figure B-4 gives C as a function of t for the same system, and in Figure B-5 the ΔC ratios plot to the same straight line.

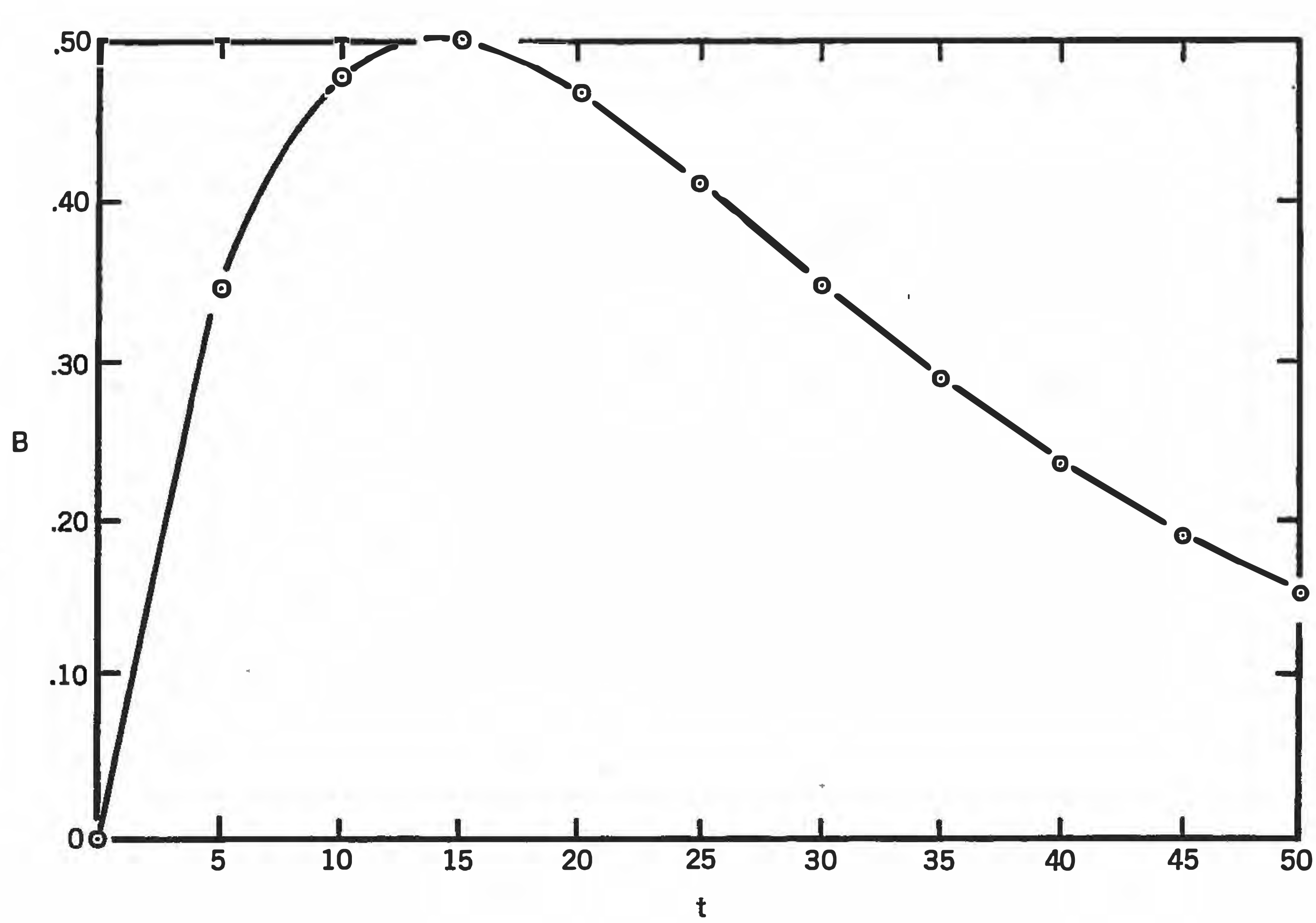


FIGURE B-2

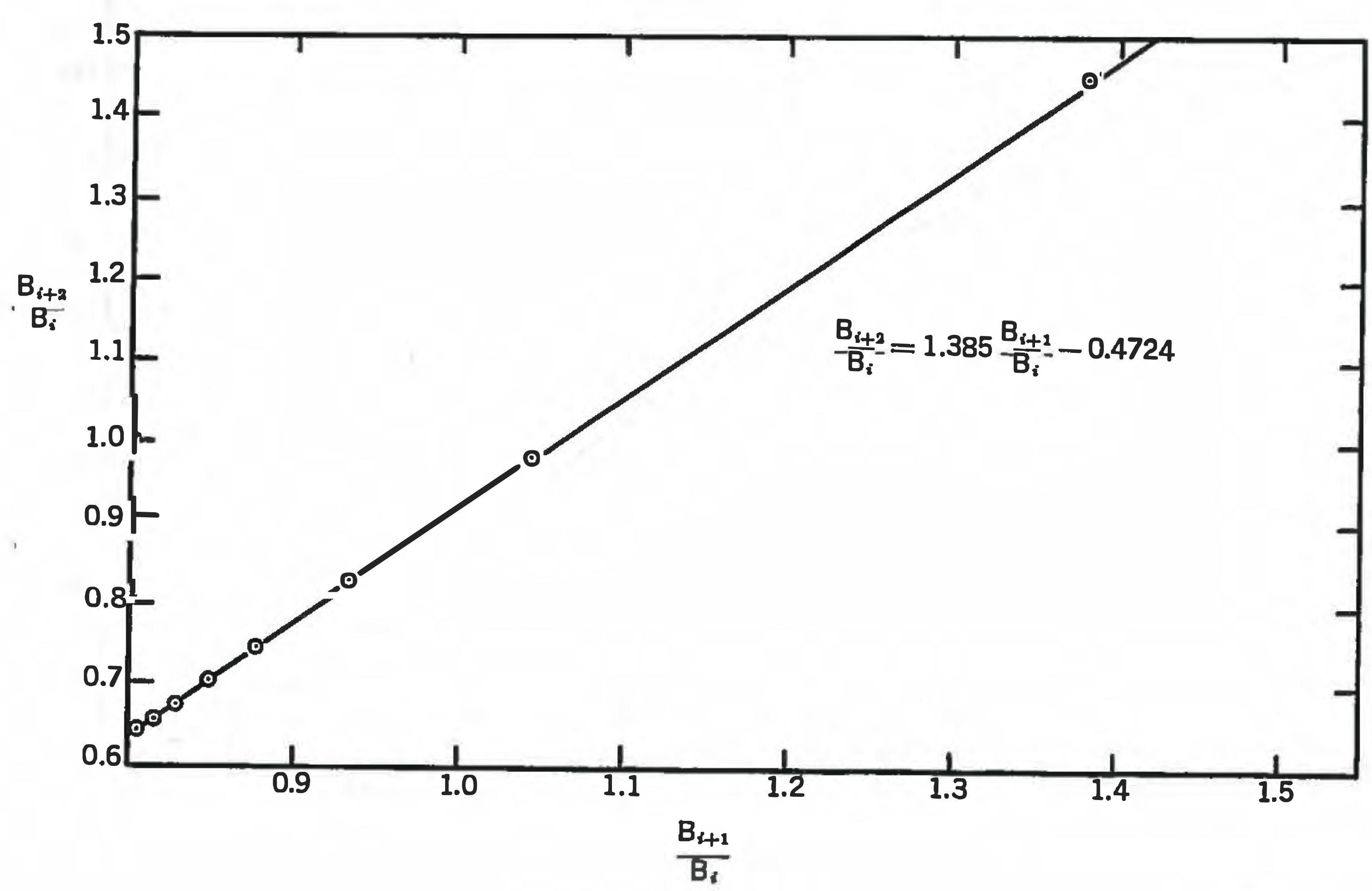

1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.9
1.0
1.1
1.2
1.3
1.4
1.5
$\frac{B_{i+2}}{B_i}$
$\frac{B_{i+2}}{B_i} = 1.385 \frac{B_{i+1}}{B_i} - 0.4724$
$\frac{B_{i+1}}{B_i}$

FIGURE B-3

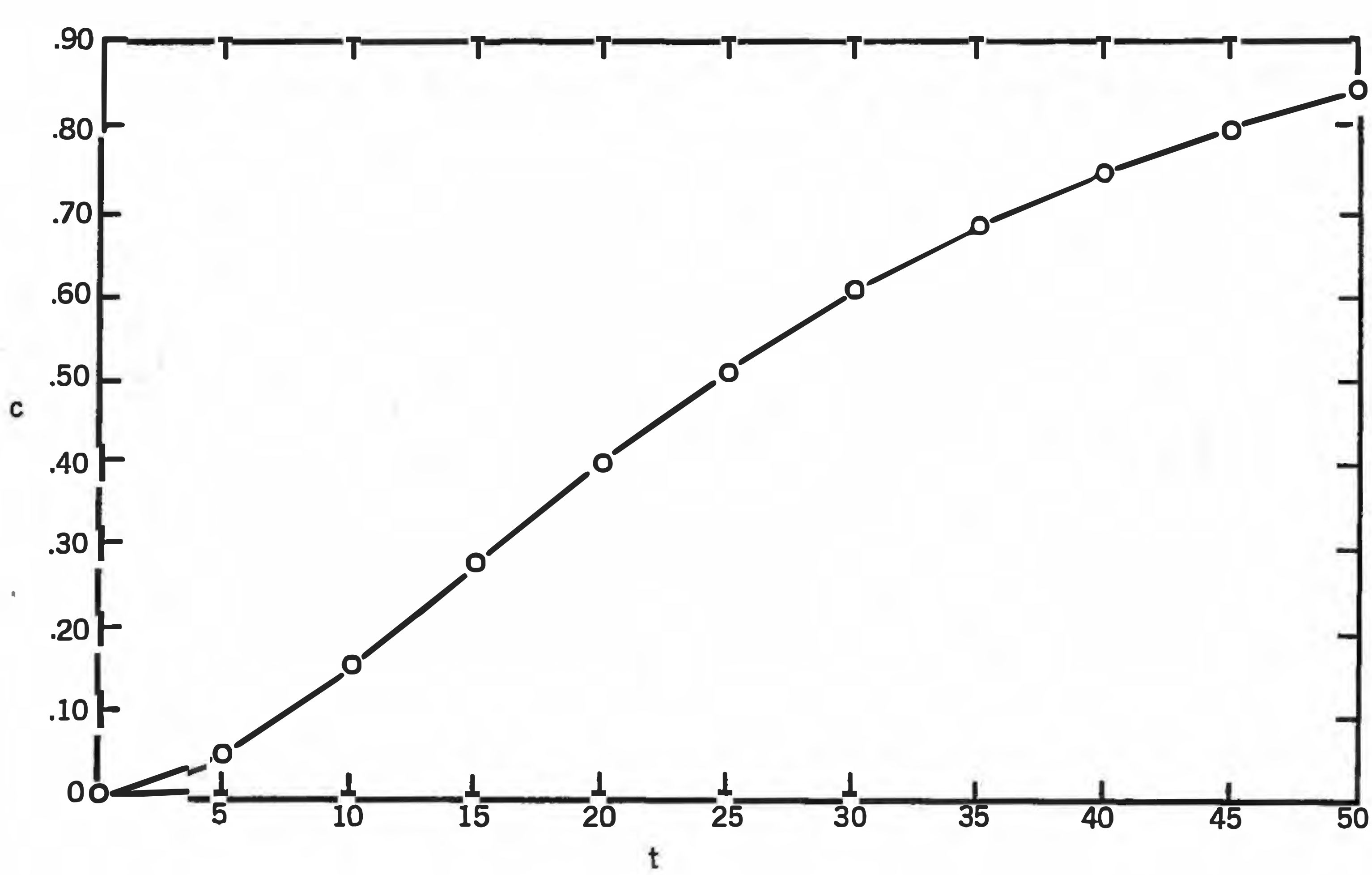


FIGURE B-4

historical data on six industrial research projects

The cooperation of a very large industrial research organization was secured and historical data on six of their research projects given us. This data is given, and the terms defined, in Table B-I. The derived straight lines, found by the method described, are presented in Figures B-6 to B-11 following. It will be noted that in spite of the scatter in the right hand portion of the curves (which are generated by the left hand portion of the growth curves, i.e., the early stages of the work where small errors are large relative to the true value) a reasonably good fit to straight lines is observed. Thus it may be concluded that the rate at which the work was carried on, representing an experienced research management's judgment as to the optimum allocation of its available effort, can be consistent with the model proposed. For purposes of comparison, all of the fitted straight lines are plotted together in Figure B-12, and it will be observed that the lines all lie within a very narrow range. The k values cannot be calculated from these data, the absolute time scale being unknown, but the coincidence of the straight lines would indicate that the ratio k_1/k_2 is close to being constant. This might mean a consistent research managerial policy, or it might indicate that the ratio is in fact characteristic of the field of science wherein the work lies.

Up to this point it has been assumed that k_1 and k_2 are constants. In this case, as we have just shown, their values can be evaluated. In general, however, the amounts of effort put into the two stages may vary with time. Under such circumstances it is reasonable to assume that the rate of each step is proportional to the effort (E_1, E_2) put into that stage. If this is the case, the rate equations are modified to become

$$dA/dt = -k_1E_1A \qquad (8a)$$

$$dB/dt = k_1E_1A - k_2E_2B \qquad (8b)$$

$$dC/dt = k_2E_2B \qquad (8c)$$

where k_1 and k_2 are proportionality constants. The larger the magnitude of these constants, the greater the ease of the corresponding processes. Note that E_1 and E_2 are both generally functions of time.

One integral of these equations is found immediately by adding the three equations. It is the conservation law

$$A + B + C = A_o \qquad (9)$$

The complete solution of these equations is most conveniently expressed in terms of the quantities F_1 and F_2 defined by

$$F_1 = \int_0^t E_1 dt \qquad (10a)$$

$$F_2 = \int_0^t E_2 dt \qquad (10b)$$

Physically, F_1 is the total effort put into basic research up to time t, and

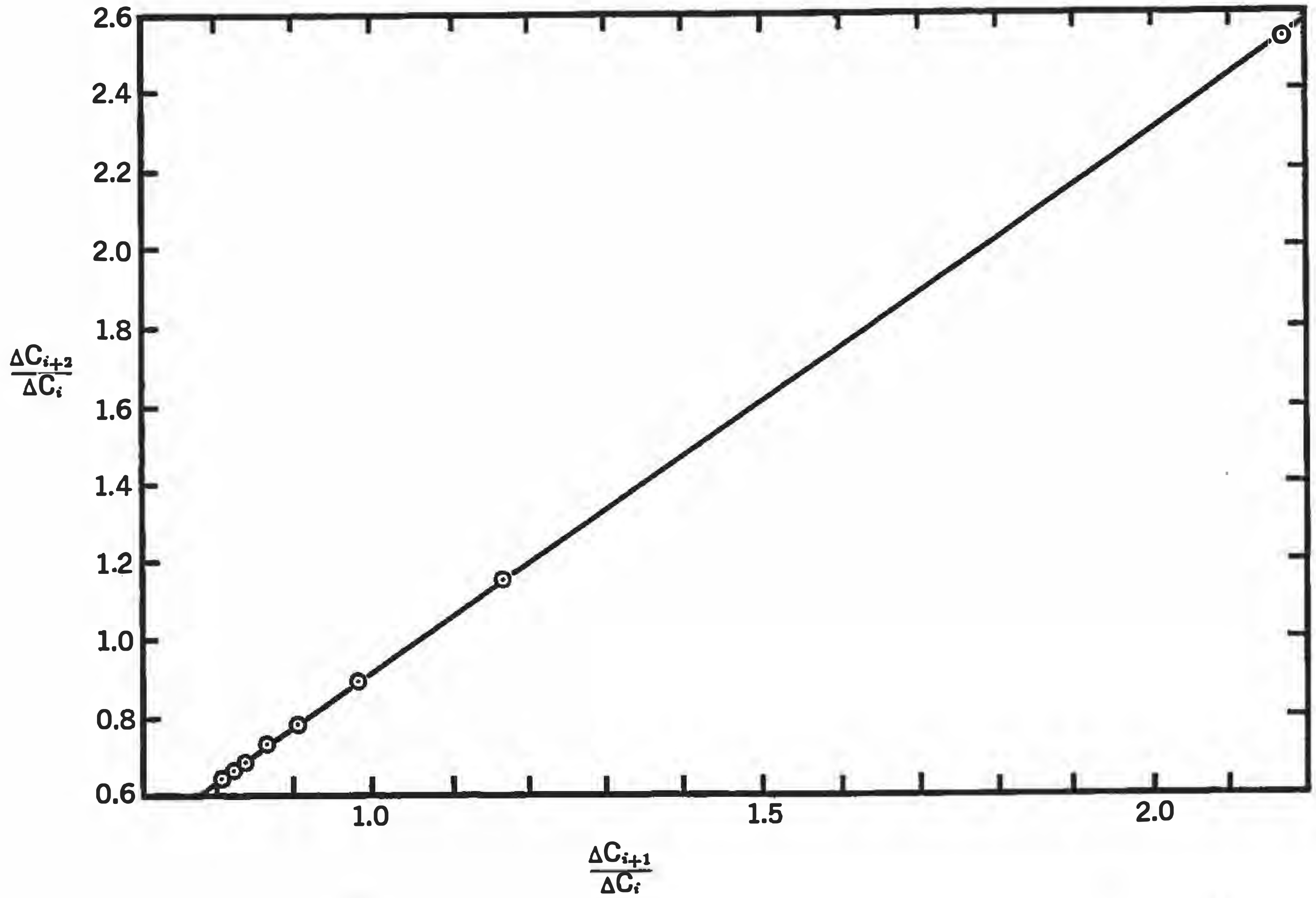
TABLE B-1

The Development Effort* Utilized on Various Projects, Plotted as a Percent of the total Effort Utilized at Given Percentages of Calendar Time Required to Complete the Project.

Percent of Calendar Time	Percent of Total Development Effort Utilized					
	I	II	III	IV	V	VI
5.0	0.6	0.3	0.8	0.6	0.5	0.6
10.0	1.5	0.7	2.0	1.8	1.0	1.4
15.0	2.3	1.2	4.1	3.1	1.8	2.3
20.0	3.5	2.2	7.3	4.9	2.8	3.5
25.0	5.6	3.9	11.0	7.8	4.1	5.4
30.0	8.9	6.0	15.7	12.9	6.5	8.7
35.0	12.5	8.1	20.9	19.3	10.1	12.6
40.0	15.5	11.3	26.9	26.7	14.6	17.3
45.0	18.5	15.9	34.2	34.4	20.3	22.8
50.0	22.3	22.6	42.1	42.1	25.9	29.6
55.0	27.7	31.4	48.9	50.4	33.3	37.9
60.0	34.8	41.7	56.0	58.4	41.8	45.7
65.0	43.1	51.9	63.3	65.9	49.6	53.7
70.0	52.1	61.0	70.5	73.0	57.3	61.6
75.0	61.4	69.5	77.6	79.9	65.5	69.0
80.0	70.4	77.2	84.7	86.9	73.4	76.1
85.0	78.9	84.1	91.9	92.5	81.0	83.3
90.0	86.8	89.8	95.7	95.3	88.3	89.6
95.0	94.2	94.9	98.4	98.2	94.8	94.9
100.0	100.0	100.0	100.0	100.0	100.0	100.0

* Development Effort is defined as all engineering effort, technical assistance and shop time arising within the Product Development Laboratory to the point where the project was 100% released.

N. B. Projects I, II, V and VI are generically similar projects resulting in major products. Project III was run as an adjunct to Project II. It resulted in a minor product. Project IV resulted in a major product that was never marketed.



2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
$\frac{\Delta C_{i+2}}{\Delta C_i}$
1.0
1.5
2.0
$\frac{\Delta C_{i+1}}{\Delta C_i}$

FIGURE B-5

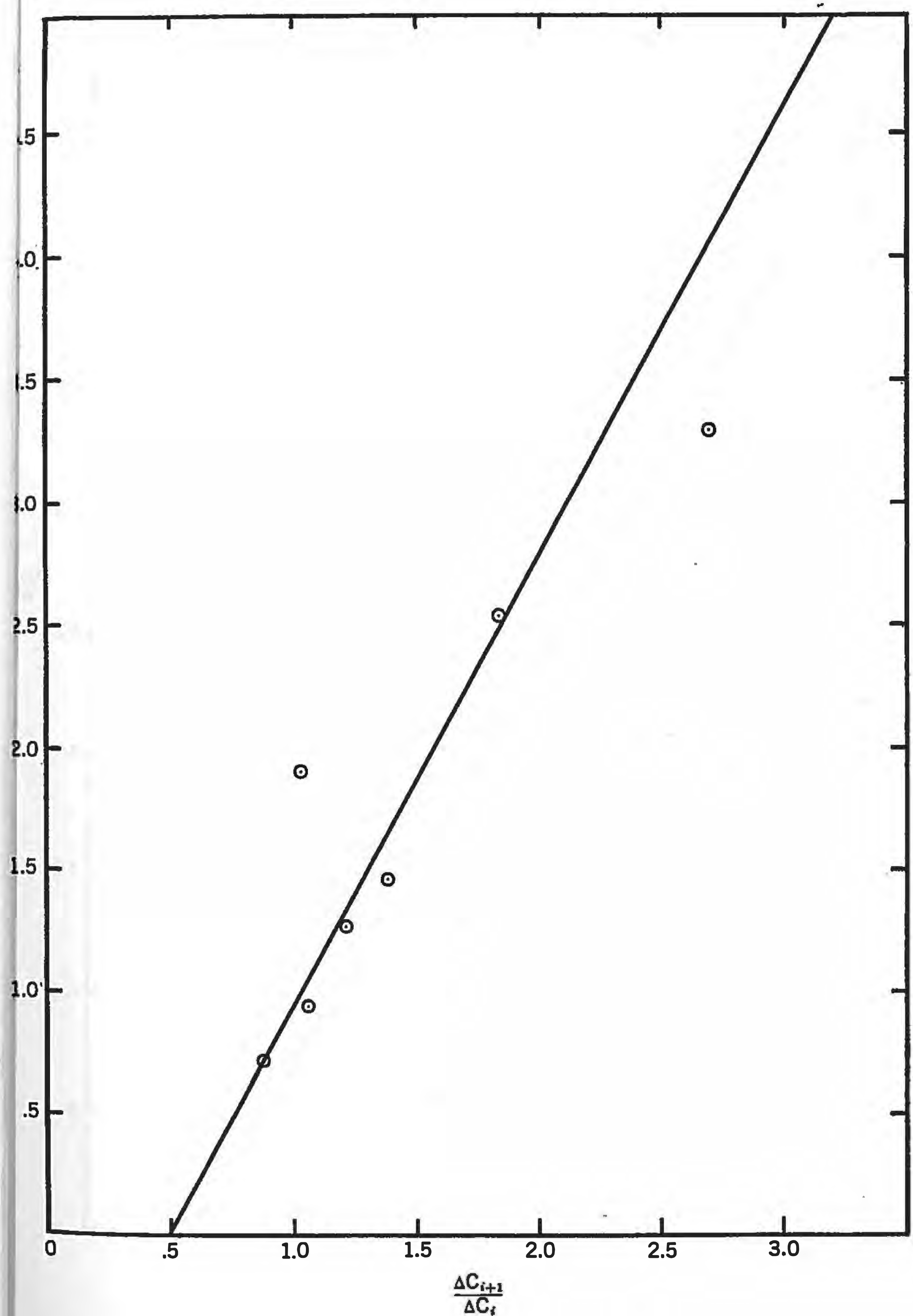


FIGURE B-6
PROJECT I

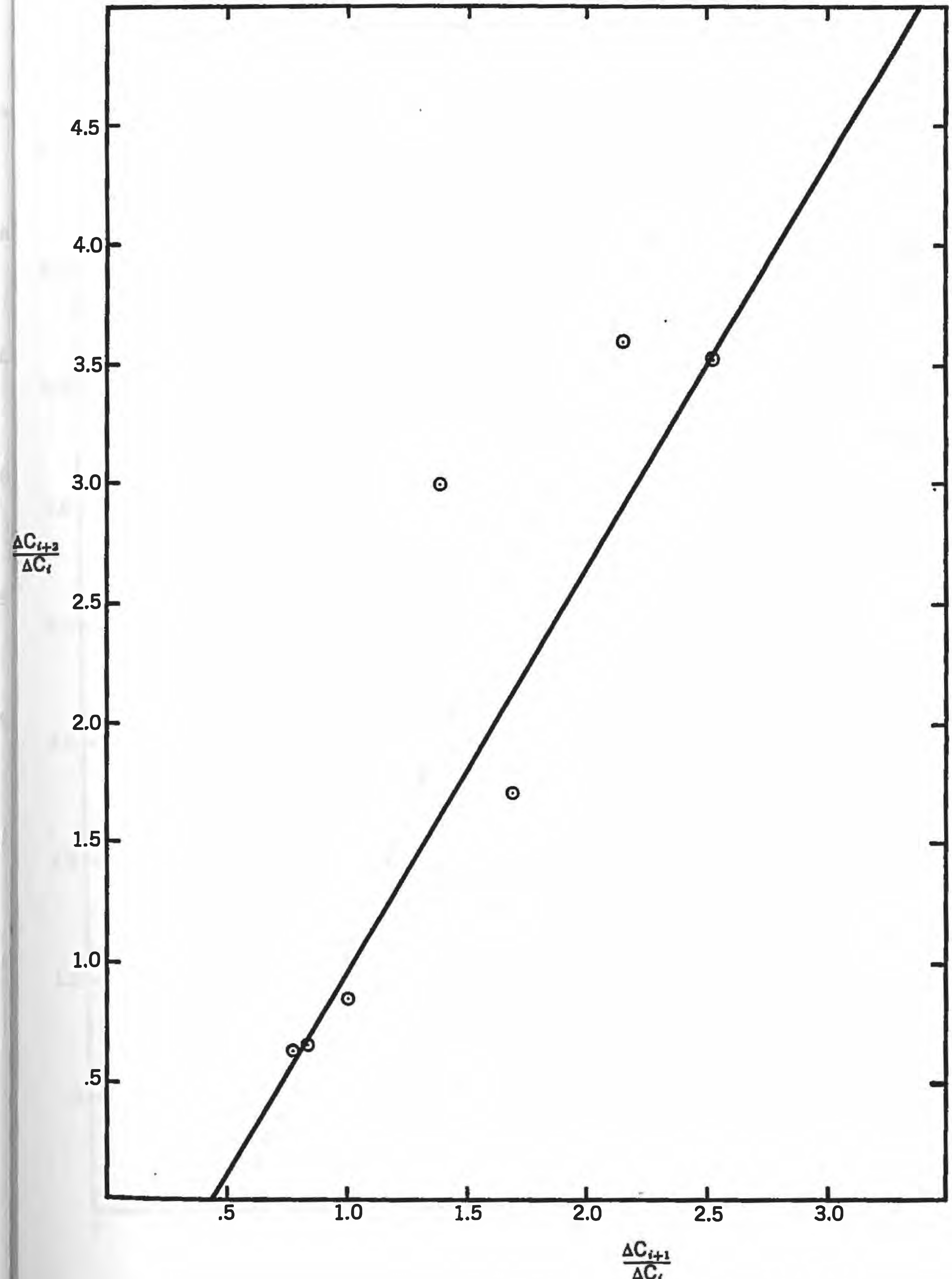


FIGURE B-7
PROJECT II

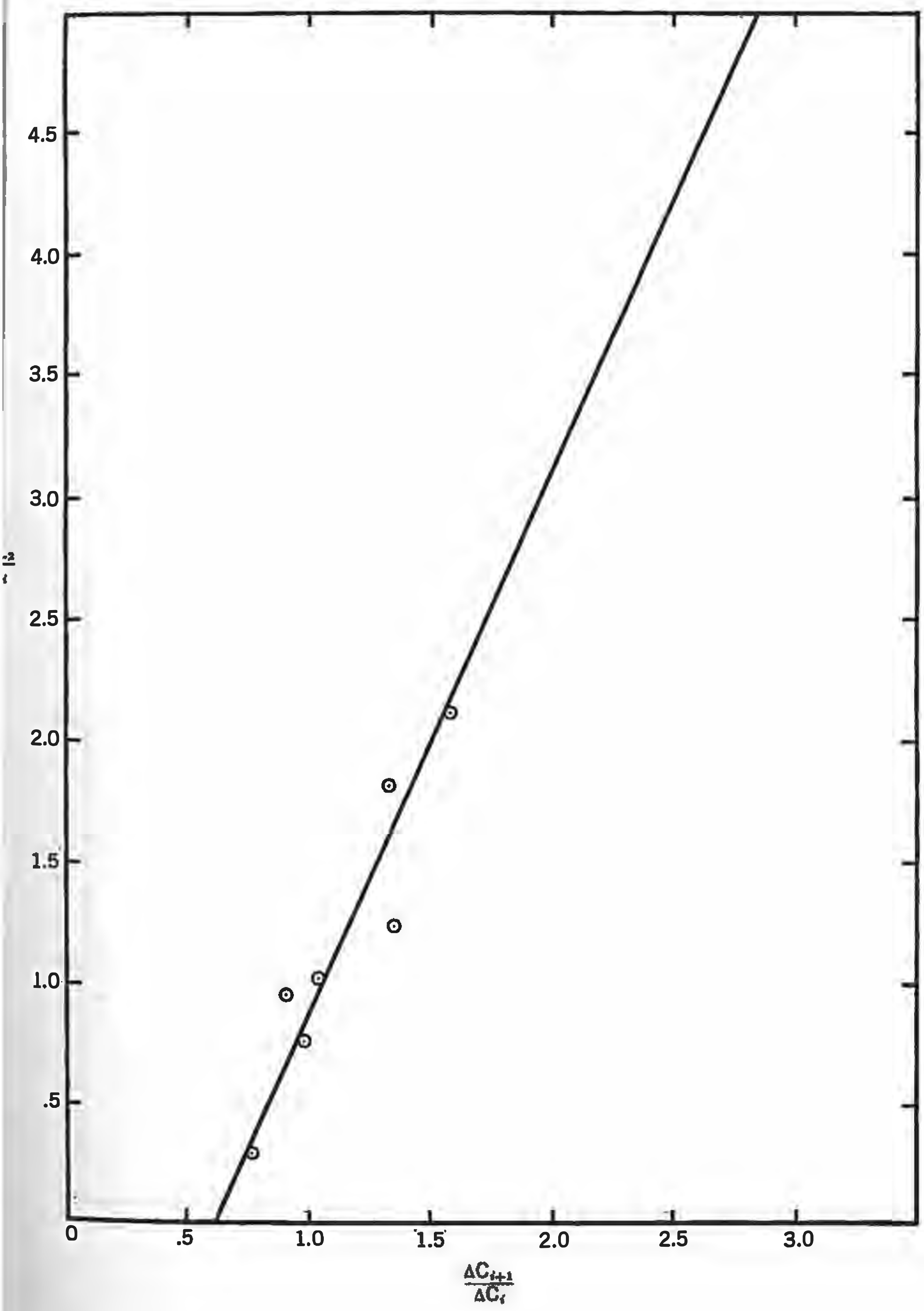
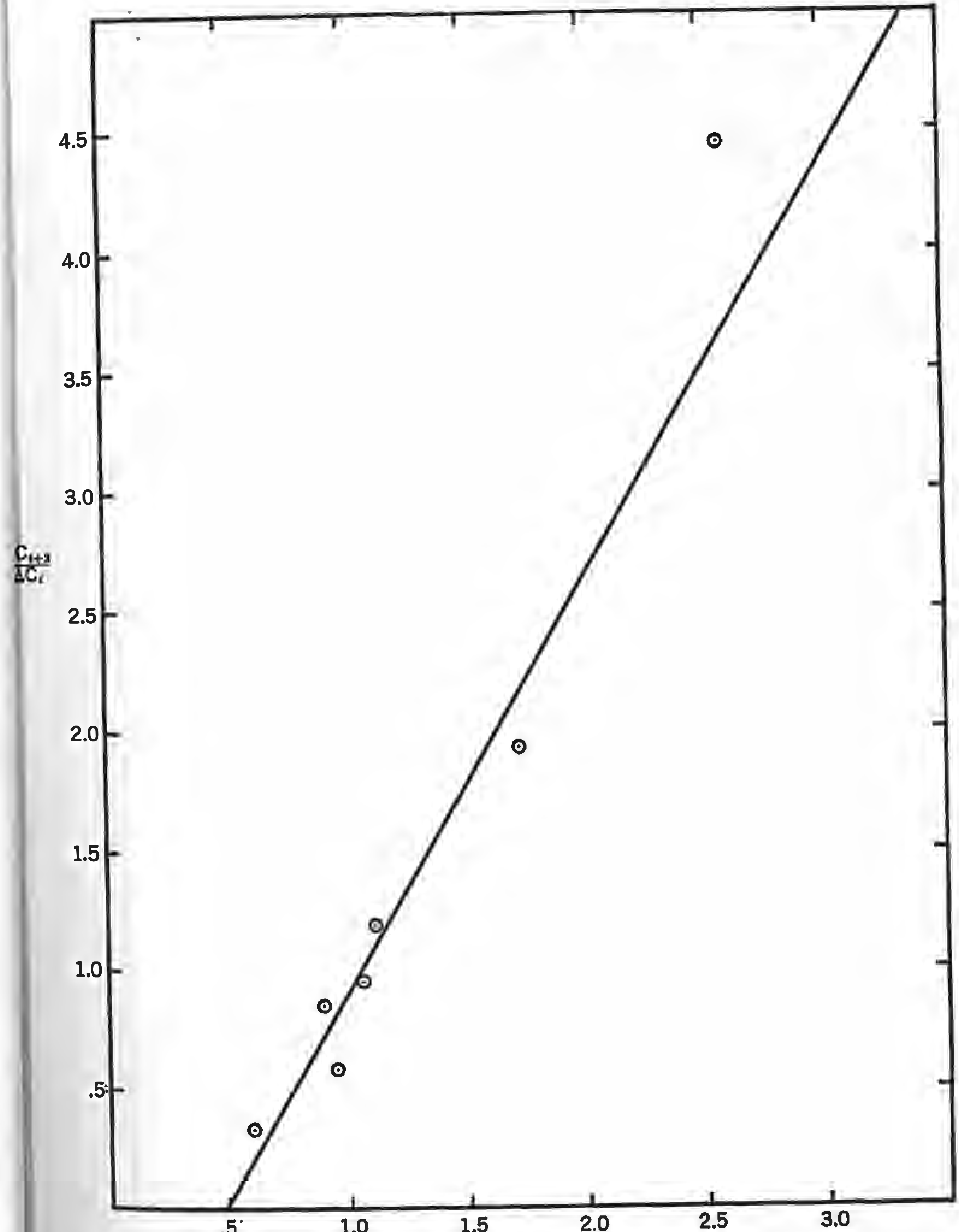


FIGURE B-8
PROJECT III



$\frac{\Delta C_{t+1}}{\Delta C_t}$

FIGURE B-9
PROJECT IV

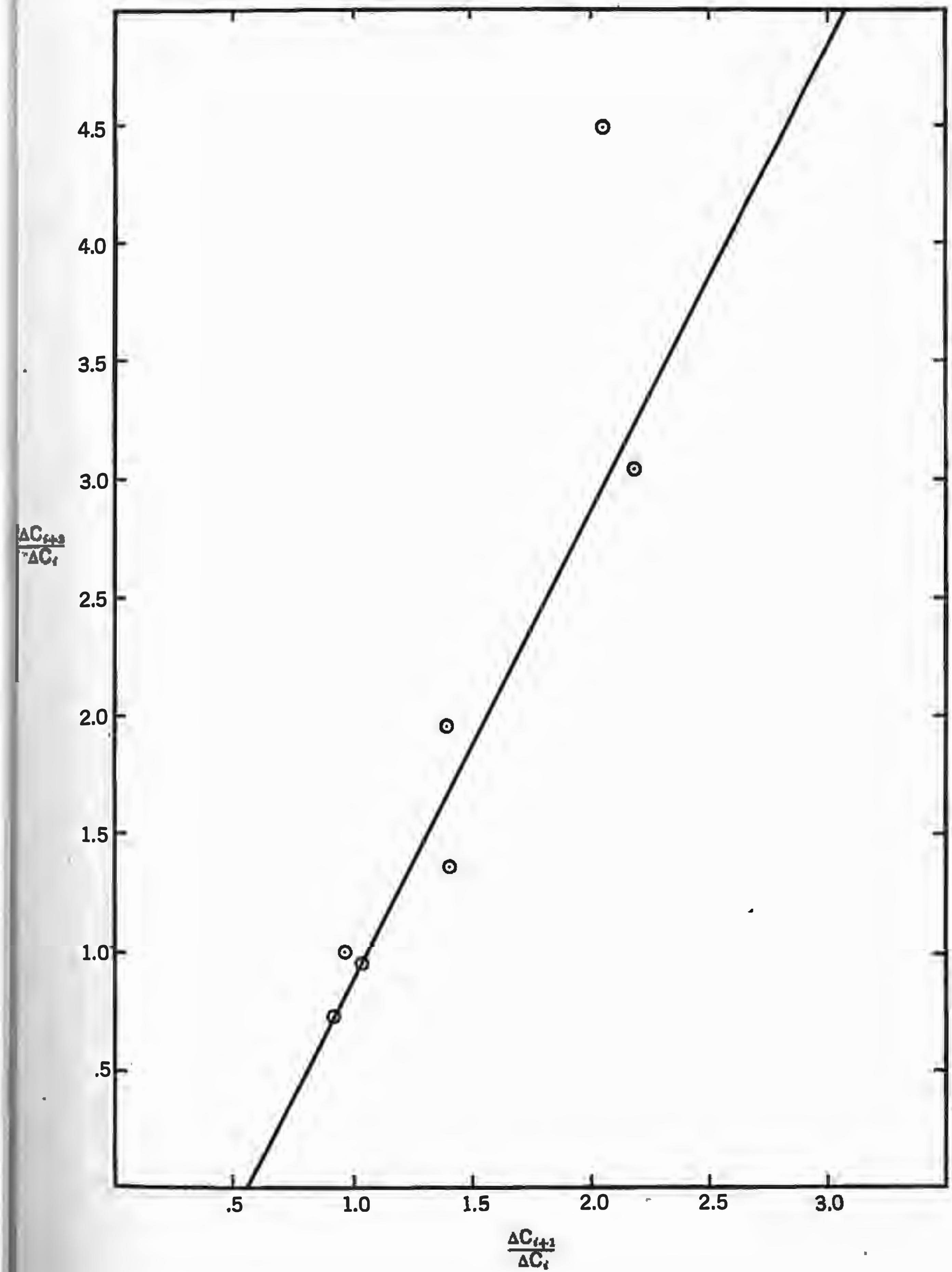


FIGURE B-10
PROJECT V

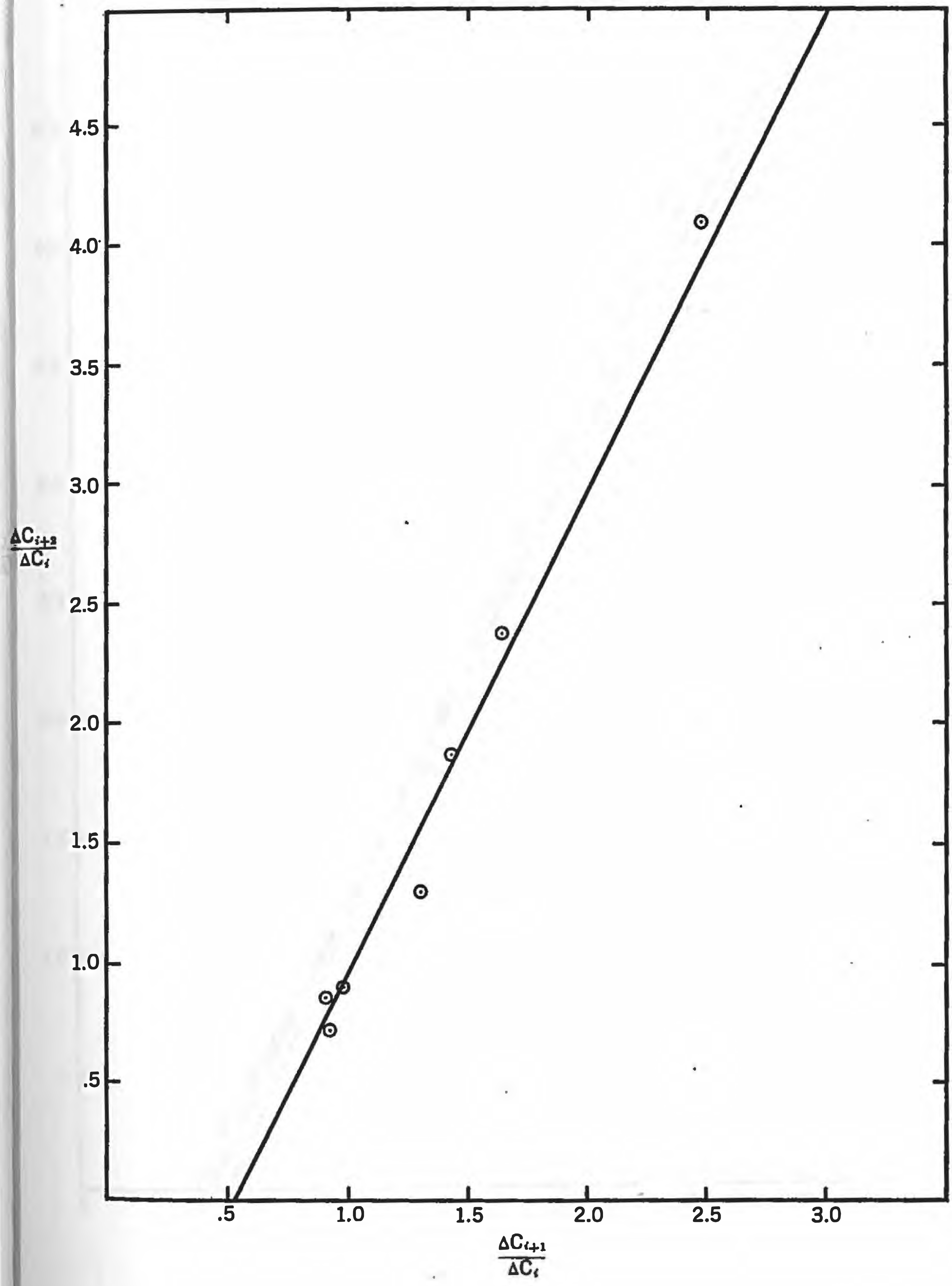


FIGURE B-11
PROJECT VI

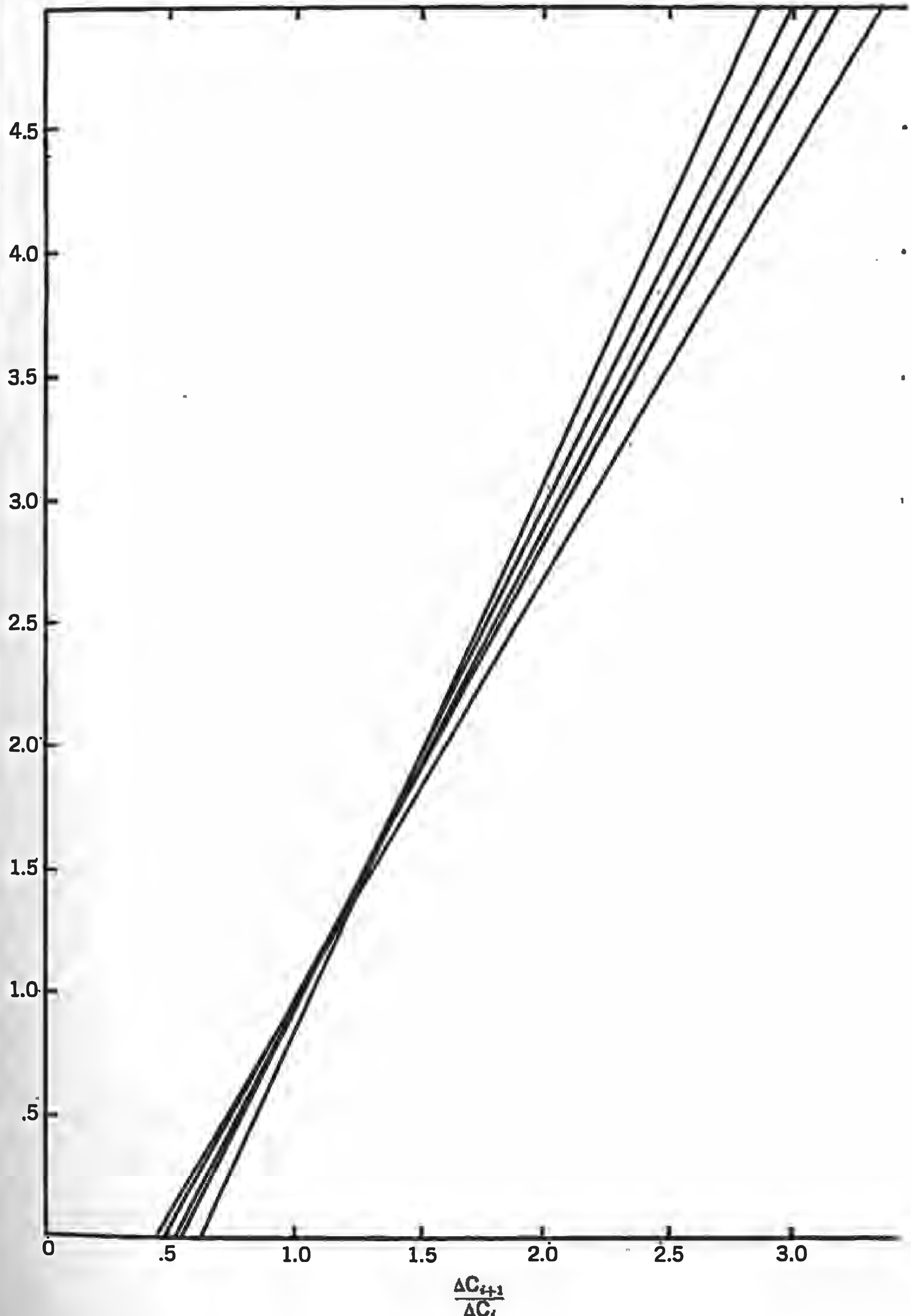


FIGURE B-12
PROJECTS I–VI

F_2 is the total effort put into applied research up to the same time. In terms of these

$$A = A_0 e^{-k_1 F_1} \tag{11a}$$

$$B = e^{-k_2 F_2} \int_0^t k_1 E_1(t_1) A(t_1) e^{k_2 F_2(t_1)} dt_1 \tag{11b}$$

$$C = A_0 - A - B \tag{11c}$$

If E_1 and E_2 are constant, these become

$$A = A_0 e^{-k_1 F_1} \tag{12a}$$

$$B = \frac{k_1 F_1 A_0}{k_2 F_2 - k_1 F_1} (e^{-k_1 F_1} - e^{-k_2 F_2}) \tag{12b}$$

$$C = A_0 \left[1 - \frac{k_2 F_2 e^{-k_1 F_1} - k_1 F_1 e^{-k_2 F_2}}{k_2 F_2 - k_1 F_1} \right] \tag{12c}$$

but it is not necessarily desirable for E_1 and E_2 to be held constant. In equation (11b), the factor $e^{k_2 F_2(t_1)}$ in the integral is equal to or greater than unity, since F_2 is necessarily positive. Hence

$$B \geq B_1 \tag{13}$$

where

$$\begin{aligned} B_1 &= e^{-k_2 F_2} \int_0^t k_1 E_1(t_1) A(t_1) dt_1 \\ &= e^{-k_2 F_2} \int_0^t \left(-\frac{dA}{dt_1} \right) dt_1 \\ &= e^{-k_2 F_2} (A_0 - A) \\ &= A_0 e^{-k_2 F_2} (1 - e^{-k_1 F_1}) \end{aligned} \tag{14}$$

and if we put

$$C_1 - A_0 - A - B_1 = A(1 - e^{-k_1 F_1})(1 - e^{-k_2 F_2}) \tag{15}$$

then

$$C \leq C_1 \tag{16}$$

It follows that a knowledge of the total efforts F_1 and F_2 up to a certain time puts an upper limit C_1 to the total number of applications. How nearly this upper limit is reached depends on the timing. For example, if all the applied effort F_2 is used before any of the basic effort F_1, then equations (11) give

$$\begin{aligned} A &= A_0 e^{-k_1 F_1} \\ B &= A_0 (1 - e^{-k_1 F_1}) \\ C &= 0 \end{aligned}$$

and no useful results are obtained.

The upper limit is reached if, and only if, all the basic research effort is completed before any of the applied effort is started. To do otherwise is therefore wasteful, although it may be required by other considerations.

how to divide a fixed total effort between basic and applied research

We can now attack the problem of how to divide a fixed total effort between basic and applied research. Suppose that it is desired to divide a given total F between F_1 and F_2 so as to maximize C. If the research can be done sequentially, this will reduce to the problem of maximizing C_1 subject to the condition that

$$F_1 + F_2 = F \tag{17}$$

To solve this problem, it will be convenient to put

$$B_1 = 1 - e^{-k_1F_1} \tag{18a}$$

$$B_2 = 1 - e^{-k_2F_2} \tag{18b}$$

Then

$$C_1 = A_o B_1 B_2 \tag{19}$$

and we can interpret B_1 as the fraction of A_o converted to B, and B_2 as the fraction of the B converted into C. Equations (18) can be inverted to give

$$F_1 = \frac{1}{k_1} \ln \frac{1}{1 - B_1} \tag{20a}$$

$$F_2 = \frac{1}{k_2} \ln \frac{1}{1 - B_2} \tag{20b}$$

The maximum problem is then to find B_1 and B_2 such that

$$B_2 dB_1 + B_1 dB_2 = 0 \tag{21}$$

for arbitrary dB_1 and dB_2 subject to the condition

$$\frac{1}{k_1}\frac{dB_1}{1 - B_1} + \frac{1}{k_2}\frac{dB_2}{1 - B_2} = 0 \tag{22}$$

This reduces to

$$\frac{k_1 (1 - B_1)}{B_1} = \frac{k_2(1 - B_2)}{B_2} \tag{23}$$

as the equation which must be satisfied by the B's at the maximum. In order to compute with these equations, let us define

$$k = \sqrt{k_1 k_2} \tag{24}$$

and

$$\frac{k_1}{k} = \frac{k}{k_2} = \sqrt{\frac{k_1}{k_2}} \tag{25}$$

If we also put

$$\frac{k}{\lambda} = \frac{k_1(1 - B_1)}{B_1} = \frac{k_2(1 - B_2)}{B_2} \tag{26}$$

Then in terms of λ and ρ we find

$$B_1 = \frac{\rho\lambda}{1 + \rho\lambda} \tag{27a}$$

$$B_2 = \frac{\rho^{-1}\lambda}{1 + \rho^{-1}} \tag{27b}$$

$$B_1 B_2 = \frac{\lambda^2}{(1 + \rho\lambda)(1 + \rho^{-1}\lambda)} \tag{27c}$$

$$kF_1 = \rho^{-1} \ln (1 + \rho\lambda) \tag{27d}$$

$$kF_2 = \rho \ln (1 + \rho^{-1}\lambda) \tag{27e}$$

converting a fraction of a new field into applied results

To use these equations, suppose that we wish to convert a fraction of a new field into applied results. We set $B_1B_2 = \gamma$ in equation (27c) and solve for λ. The remaining equations then determine the efforts, F_1 and F_2, which should be put into basic and applied research, and the conversion fractions B_1 and B_2.

If the total effort is to be small, γ will be small, and we have

$$\lambda = B_1B_2 = \sqrt{\gamma} \tag{28a}$$

$$B_1 = \rho\lambda \tag{28b}$$

$$B_2 = \rho^{-1}\lambda \tag{28c}$$

$$kF_1 = \lambda \tag{28d}$$

$$kF_2 = \lambda \tag{28e}$$

This shows that a small effort should be divided equally between basic and applied research, no matter what the value of γ.

In the case of a large effort, say

$$\gamma = \frac{1}{1 + E} \tag{29}$$

where E is small, then λ is large, in fact

$$\lambda = \frac{\rho + \rho^{-1} + \sqrt{(\rho + \rho^{-1})^2 + 4}}{2E} \tag{30}$$

and the limiting forms are

$$B_1 = 1 - \frac{1}{\rho\lambda} + \cdots \tag{31a}$$

$$B_2 = 1 - \frac{1}{\rho^{-1}\lambda} + \cdots \tag{31b}$$

$$kF_1 = \rho^{-1} \ln \lambda + \rho^{-1} \ln \rho + \frac{1}{\rho^2\lambda} + \cdots \tag{31c}$$

$$kF_2 + \rho \ln \lambda + \rho \ln \rho^{-1} + \frac{1}{\rho^{-3}\lambda} + \cdots \tag{31d}$$

In the limit

$$\frac{F_2}{F_1} = \rho^2 = \frac{k_1}{k_2} \tag{32}$$

so that the two efforts are inversely proportional to the corresponding k's.

a first sharp rise in "getting the field started"

The main features of this model are shown graphically in Figures B-13 and B-14. In Figure B-13 is shown the total effort required to convert a given fraction of a field into applications. There is a first sharp rise in "getting the field started." Then for most of the conversion process the results rise nearly linearly with the effort. At very high

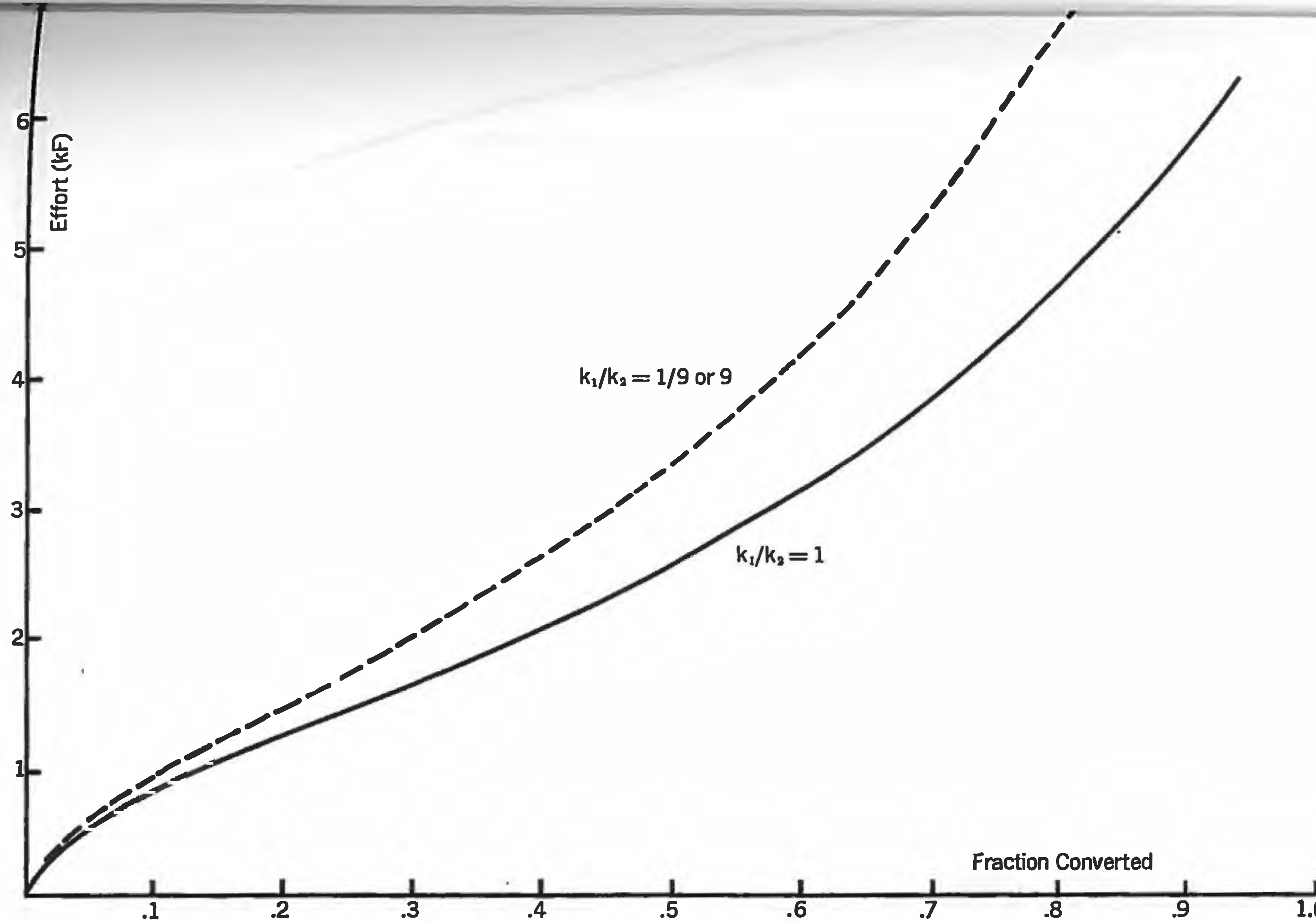


FIGURE B-13
Total Effort Required as Function of Degree of Conversion

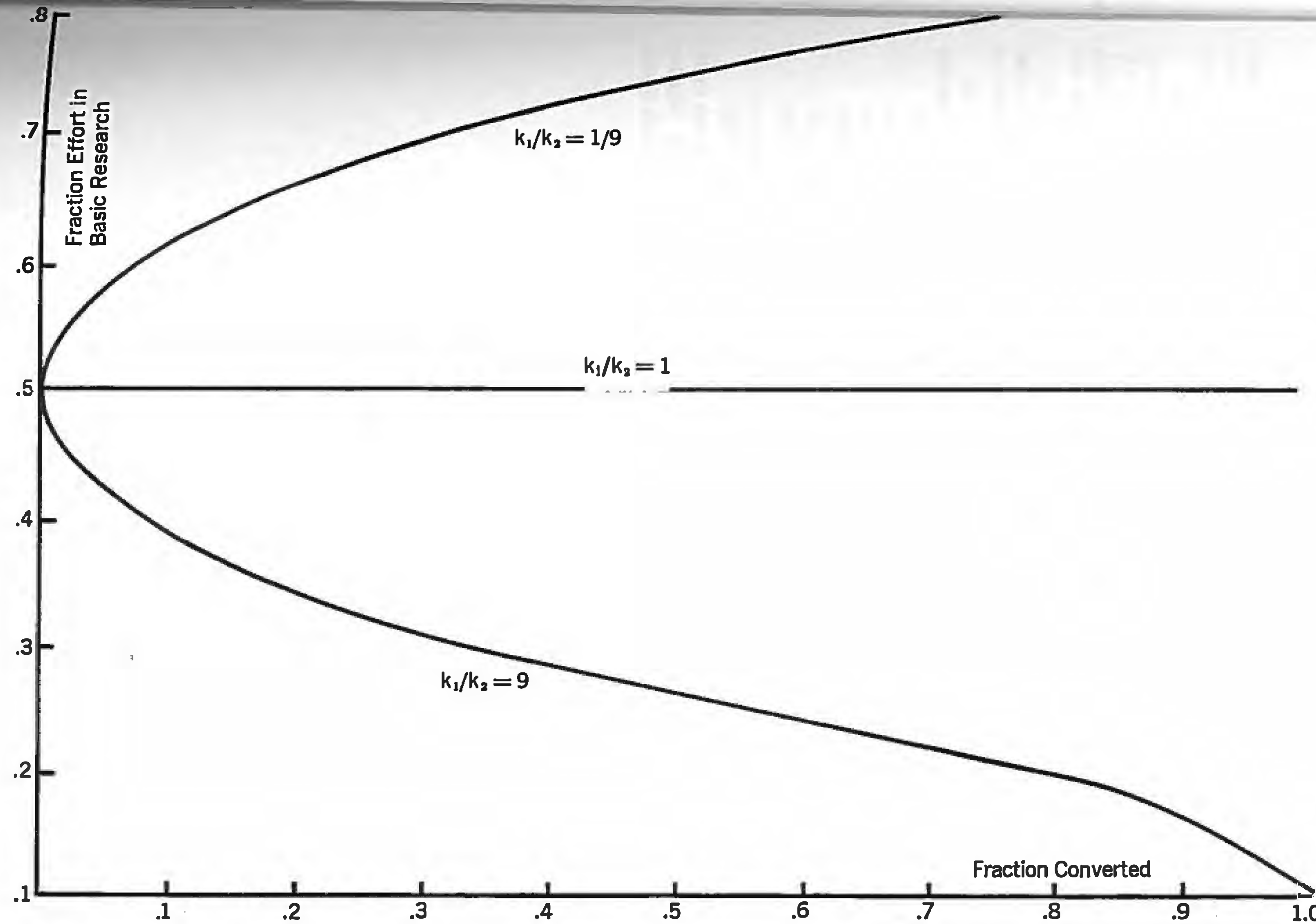


FIGURE B-14
Fraction Effort in Basic Research
as Function of Degree of Conversion

degrees of conversion, the law of diminishing returns sets in so that the effort per unit conversion rises very sharply, becoming infinite at 100% conversion.

In Figure B-14 is shown the optimum fraction of the effort which should be put into basic research. As we have pointed out previously, this is always 50% for small degrees of conversion, and approaches $k_2/(k_1 + k_2)$ at 100% conversion. For most of the intermediate range, the transition is approximately linear in the degree of conversion.

It is hard to believe that basic research is more than nine times as easy as applied research, the situation represented by the lowest curve in Figure B-14. If this model stands up, the implications are obvious.

three principal areas must be intensively investigated

Much additional work is required to elaborate this model. Three principal areas must be intensively investigated:

> The mathematics of the model must be elaborated, and the most practical method will probably involve the use of electronic computing machines to perform the numerical integrations.
>
> The relationship between time, manpower, etc., in the effort function requires considerable elaboration.
>
> Independent criteria for the measure of effectiveness must be developed before the results can be completely accepted.

Until this is done, it can only be stated that the model approach shows promise, and that the model developed is not inconsistent with the scanty data available.

Appendix C

Manpower Studies

Summary

Since 1910, research and development activities have grown at the rate of 10% per year, while the number of scientists and engineers has increased at the rate of 5% per year. If these trends persist, a serious shortage of technical manpower may develop in the near future.

In the past 25 years the number of science doctorates has increased at a rate comparable with other non-scientific fields. Barring major changes in educational policies, it now appears that for a more rapid growth in scientific manpower, the number of students in other educational disciplines will have to increase correspondingly.

At the present time, 2% of all engineers and scientists are engaged in basic research activities, 25% in research and development.

The major performers of basic research are educational institutions, which account for 60% of the total; industry accounts for 30% and Government for 10%.

Research and development expenditures per research worker average $25–30,000 in Government and industry, and $13–15,000 in educational institutions.

Publications in scientific journals are a useful measure of basic research activity. A strong correlation exists between number of publications and the scientific reputation of individual scientific workers.

Using publication rate as the measure of scientific productivity, we find that 20–30% of all scientists with Ph.D. degrees in astronomy, chemistry, and physics contribute over 80% of the basic research results in their respective fields of specialization.

Comparison of basic research expenditures in Government and industry indicates that large industrial firms in fields of high product obsolescence and rapid technological progress have increased basic research activities at a faster rate than Government agencies during the past decade.

The Navy Department is the most research-minded of the three armed services. With one-quarter of the research and development budget of the Department of Defense, the Navy Department accounts for two-thirds of the basic research activities performed in Government laboratories.

A significant increase in basic research effort can be achieved by expansion of the Contract Research Programs of Government agencies and private foundations. According to the Coordinating Committee of Science of the Department of Defense, budget increases of 70% are justified by the number of meritorious proposals rejected for lack of available funds.

Introduction

Basic research is performed by scientists and engineers with adequate educational background and professional experience. But not every competent scientist and engineer is engaged in basic research. As we will see in subsequent sections, basic research absorbs only a relatively small percentage of all qualified individuals. Applied research, development, production, administration, and teaching place much greater manpower demands on the scientific community.

estimate the basic research potential of the United States

The objective of this appendix is to estimate the basic research potential of the United States as measured by the availability of scientists and engineers. This problem has been the subject of many studies by Government agencies and private institutions. In recent years the National Science Foundation has been particularly active in this field. Most of these studies are unsatisfactory for our purpose because they do not distinguish basic research from other scientific activities. That such a distinction can be made is not generally conceded. It is often asserted that this distinction is artificial because the terms "basic" and "applied" refer to a continuous spectrum of activities ranging from work of a very fundamental nature to inconsequential gadgetry. While there undoubtedly exist borderline areas where subjective criteria must determine the side of the line on which a research project falls, this region of uncertainty is relatively narrow and does not interfere seriously with the classification of research. We are led to this conclusion by the following considerations:

> The results of most basic research studies are published in scientific journals. Security restrictions may delay publi-

cation, but seldom for more than a few years. Since editorial boards consist of competent scientists, there is remarkable agreement between scientific opinion and the editorial policy of the journals in each field of specialization. Scientific results not published in basic research journals can be assumed not to be of basic research nature.

Given a list of research projects, each one described in a paragraph or less, most scientists are in agreement as to which projects belong to basic and which to applied research.

Research Expenditures

As the first step in this study we will review research expenditures in the United States. Research expenditures are a practical and unambiguous measure of research activity. Since, however, these data are collected under varying conditions, and since differences of opinion exist as to the definition of basic research and applied research activities, we have examined two other factors correlated with research and development effort: a) number of scientists employed and b) number of scientists active in basic research, as measured by the number of papers published in scientific journals of recognized reputation.

the major performers of scientific research are government laboratories, industry, and educational institutions

The three major performers of scientific research in the physical sciences are Government laboratories, industry, and educational institutions. In 1953–54 the National Science Foundation conducted a survey of research and development activities in every sector of the economy.[1] A summary of the results is tabulated below:

TABLE C-I

Results of National Science Foundation Survey

Performers of Research	R & D Expenditures (M $)	Basic Research Expenditures (M $)
Government	970	47
Industry	3870	168
Educational and Non-Profit Institutions	460	205
Other	70	14
Total	5370	435

According to this survey, industry accounts for the bulk of the research and development effort, including both civilian and military projects

[1] ...th Annual Report, 1957, National Science Foundation, pp. 6–8

educational and other non-profit institutions are leaders in basic research

financed by the Department of Defense and other Government agencies.

Basic research represents 8% of research and development expenditures. In basic research, educational and other non-profit institutions are undisputed leaders. The sources of financial support for research activities are shown in Table C-II, based again on the National Science Foundation survey of 1953–54. Government and industry share almost equally in support of research, and academic institutions rely heavily on Government and industry sponsorship.

TABLE C-II

Sources of Research Funds

Sources	R & D Expenditures (M $)	Basic Research Expenditures (M $)
Government	2810	158
Industry	2370	179
Educational and Non-Profit Institutions	130	60
Other	50	38
Total	5370	435

Research and Development Personnel

Current Government estimates [2] place the number of scientists and engineers employed in the United States at 750,000. Of this total, 200–230,000 are engaged in research and development activities.[3, 4] The remainder are in production, teaching, administration, etc. Table C-III shows the percent of scientists and engineers in research and development by field of specialization.[5]

The employment of research and development personnel has been studied by the National Science Foundation[6] on the basis of 1953 data. Results are shown in Table C-IV.

[2] "Engineering and Scientific Manpower in the United States, Western Europe, and Soviet Russia," Joint Committee on Atomic Energy, 1956.

[3] Scientific Personnel Resources, National Science Foundation, 1955, p. 22.

[4] Reviews of Data on Research and Development, National Science Foundation, February, 1958.

[5] Scientific Personnel Resources, National Science Foundation, 1955, p. 22.

[6] Ibid, p. 20.

TABLE C-III

Scientists in Research and Development

Field	Percent of Scientists in R & D
Astronomers	37
Biologists	32
Chemists	45
Engineers	25
Geologists	58
Geophysicists	56
Mathematicians	15
Meteorologists	12
Physicists	47

TABLE C-IV

Employment Distribution of Research and Development Scientists and Engineers

Type of Employer	Percent
Government	17
Industry	68
Educational and Non-Profit Institutions	15

The comparison of Tables C-I and C-IV reveals that Government laboratories account for 18% of all research and development expenditures and for 17% of the technical personnel engaged in these activities; industry for 72% of research and development expenditures and 68% of the technical personnel; educational institutions for 9% of the expenditures and 15% of the personnel. An equivalent interpretation of these relationships is presented in Table C-V where it is shown that, according to these data, research and development expenditures per research worker are $25–30,000 per year in Government and industry and half this amount in educational and other non-profit institutions.

TABLE C-V

Research and Development Expenditures Per Research Worker

Type of Organization	Total R & D Expenditure	Research Personnel Employed	R & D Expenditures per Researcher
Government	$ 970 M	34–39,000	$25–29,000
Industry	3870 M	136–156,000	25–28,000
Educational and Non-Profit Institutions	460 M	30–35,000	13–15,000

The relatively lower cost of research conducted in educational institutions can be explained if one notes that members of academic staffs, even when their primary interest is research, devote considerable time to teaching. In addition, they rely on inexpensive student help and tend to favor research projects which do not require major outlays. Also to be noted are the lower overhead rates charged by non-profit institutions and their lower salary structure.

Scientific Potential

the number of doctorates granted has quadrupled (1932-1955)

The Association of Research Libraries publishes annually a complete list of doctoral degrees awarded by American universities. During the period 1932–1955 the number of doctorates granted each year has almost quadrupled (See Table C-VI).

TABLE C-VI

Number of Doctoral Degrees Granted by American Universities

Year	No. of Degrees	Year	No. of Degrees
1932	2368	1944	2117
1933	2462	1945	1576
1934	2620	1946	1708
1935	2649	1947	2586
1936	2683	1948	3609
1937	2709	1949	4853
1938	2768	1950	6510
1939	2928	1951	7477
1940	3088	1952	7661
1941	3526	1953	8608
1942	3243	1954	9000
1943	2689	1955	8812

Table C-VII shows the percentage of doctorates awarded in the physical and biological sciences during the same period. The remarkable constancy of these percentages indicates that the increase in scientific manpower has paralleled the increase in other non-scientific fields.

Within the various scientific disciplines there have been some notable shifts in the fields in which doctorates have been awarded. The number of engineers, physicists, and metallurgists is increasing more rapidly than the number of chemists or mathematicians (See Figure C-1). Similar shifts have occurred within the biological and social sciences and within the humanities.

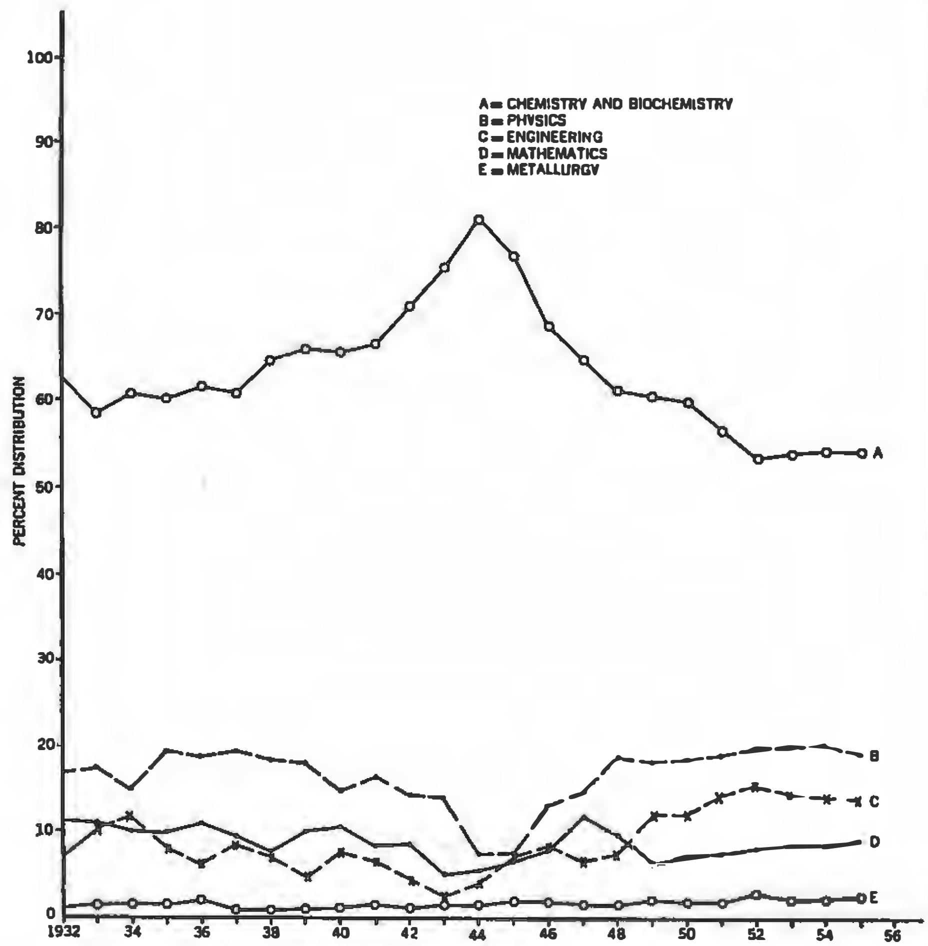


FIGURE C-1
Ph.D. DEGREES THE PHYSICAL SCIENCES

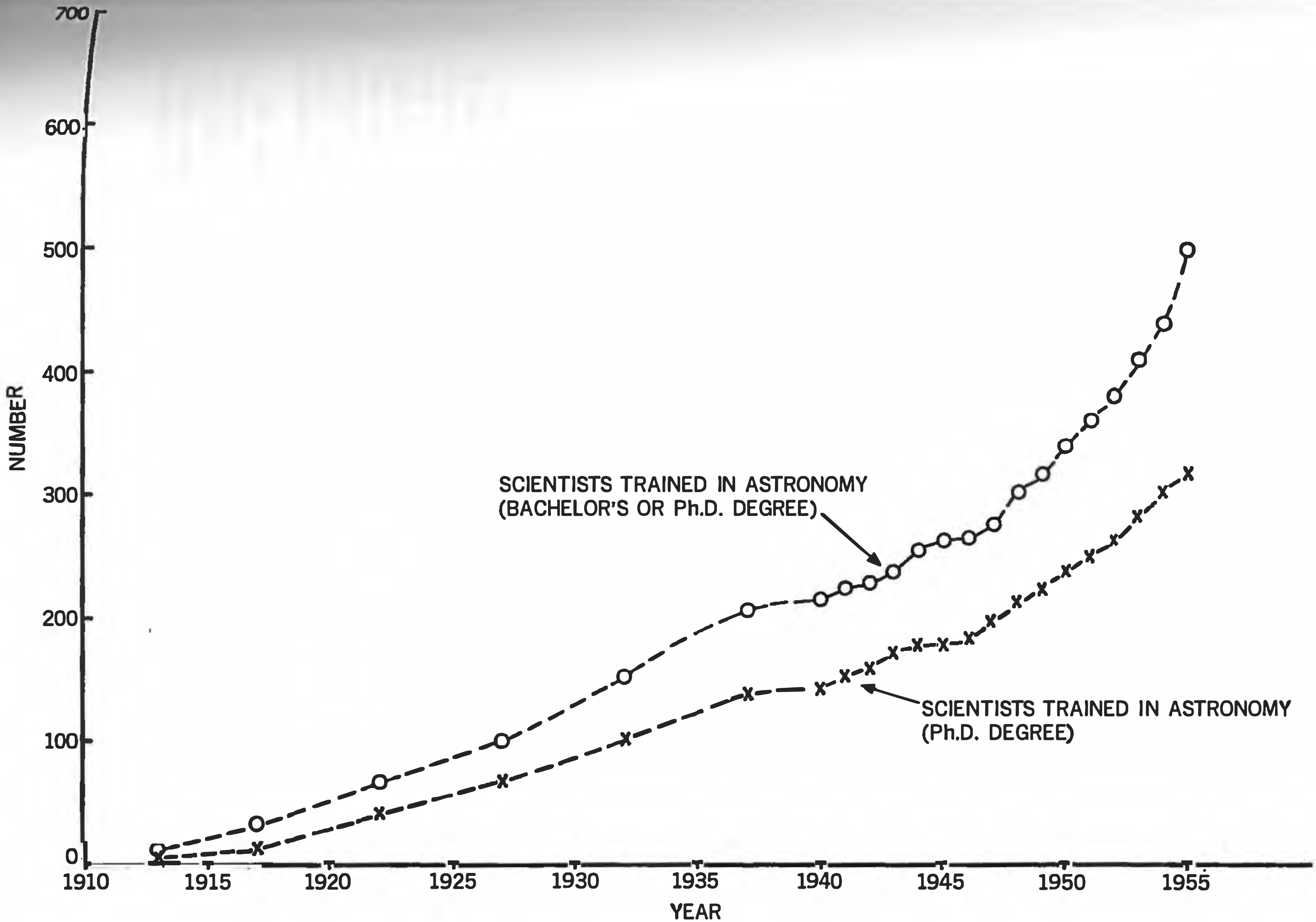


FIGURE C-2
NUMBER OF SCIENTISTS TRAINED IN ASTRONOMY

TABLE C-VII

Doctoral Degrees in the Physical and Life Sciences as Percent of All Doctoral Degrees Awarded

Year	Physical Sciences	Life Sciences
1932	30.5%	17.4%
1933	32.0	18.1
1934	34.7	20.5
1935	32.6	21.1
1936	32.0	21.2
1937	32.4	19.5
1938	28.7	22.4
1939	29.6	22.7
1940	31.0	24.0
1941	32.2	22.1
1942	29.7	22.9
1943	30.1	23.5
1944	31.6	21.3
1945	30.1	19.4
1946	29.4	18.5
1947	30.2	20.0
1948	34.0	21.4
1949	34.8	19.0
1950	33.4	19.1
1951	31.6	19.8
1952	32.2	18.9
1953	30.4	19.9
1954	29.4	20.5
1955	29.6	20.4

The picture that emerges from these data is that the absolute number of science doctorates is growing, but the relative number of science doctorates is not. There have been significant shifts within each major field of knowledge, but during the past twenty-five years the balance between the physical and biological sciences and other disciplines has been preserved. One might conclude, therefore, that, barring major changes in educational policy, for a more rapid growth of scientific manpower, the number of students in other fields will have to be increased correspondingly.

there has been no increase in relative number of science doctorates

No comparable data exists for bachelor's and master's degrees. However, estimates by the United States Department of Health, Education, and Welfare, Office of Education, indicate that the percentage of college graduates receiving doctorates has remained relatively constant at about 4% for several decades.

In the following pages we will attempt to estimate:

The number of scientists and engineers engaged in basic research.

The scientific and technical manpower potentially available.

The financial support needed to expand the basic research effort.

In order to achieve these objectives, it would be desirable to examine each scientific field individually. Lack of time and of reliable data in usable form has precluded this approach. We have limited ourselves to a few fields and extrapolated some of the results to the whole research community. We will first report on a study of astronomers. The small number of scientists active in this field has permitted us to identify them individually and review their scientific contributions.

Astronomers

The number of astronomers in the United States as been estimated in several ways:

1. The American Astronomical Society has over 700 members on its membership list. This number includes amateur astronomers as well as scientists whose primary interests are in other fields. Based on their recorded addresses, it appears that approximately 425 of the members of the Society are affiliated with university astronomy departments, observatories, etc.

2. In the 1954-55 survey, the National Register of Scientific and Technical Personnel reported 433 astronomers as holding doctor's degrees, or bachelor's degrees plus four years of scientific experience. Of these 433 astronomers, 83 were retired, inactive, on military duty, or otherwise not active professionally.

3. An estimate of the number of American scientists trained in astronomy can be computed in the following manner:

a) The number of Ph.D. degrees in astronomy granted by American universities is reported by the Association of Research Libraries.

b) The number of bachelor's degrees awarded in astronomy is 50% greater than the number of Ph.D. degrees. (According to the Office of Education, 153 bachelor's degrees and 102 Ph.D. degrees were awarded by United States universities during the period 1948–1954. Assuming that this proportion has remained constant in the past several decades, we find that two thirds of astronomers hold Ph.D. degrees. This ratio agrees with the findings of National Science Foundation studies.)

c) Astronomers retire from active professional work at age 68.

d) The mortality rate for astronomers can be established from actuarial tables.

e) The number of foreign-educated astronomers employed in the United States is balanced by the number of United States educated astronomers employed abroad. (Of all recipients of Ph.D. degrees in astronomy during the period 1936-1955, 11% are now located outside the United States. Conversely, 9% of the astronomers residing in the United States were trained at foreign universities.)

Figure C-2 presents in graphical form the number of scientists with bachelor's or Ph.D. degrees in astronomy in the years 1913–1955.

From data collected by the National Register of Technical and Scientific Personnel, from *American Men of Science*, from university and observatory reports, and from Astronomical Society membership, we have located the place of employment of most of the active astronomers. Results of this analysis are given in Table C-VIII.

TABLE C-VIII

Place of Employment of Astronomers

	Astronomers Holding Ph.D. Degrees	All Astronomers
Academic Institutions	59%	54%
Government	13	14
Industry	5	13
Inactive	23	19

Excluding graduate students, we find that approximately 300 professional astronomers were active in basic research in 1955.

As a further check we have examined all papers published in the *Astrophysical Journal*, *Astronomical Journal*, *Nature*, *The Physical Review*, *Proceedings of the Astronomical Society of the Pacific*, and *Monthly Notes*, in the years 1953–56. A total of 203 astronomers residing in the United States published one or more papers (as sole authors or co-authors) in the four-year period. Table C-IX shows the number of astronomers who published one, two, three, etc. papers during this period in the journals considered.

TABLE C-IX

Frequency Distribution of Publication in Astronomy By U. S. Astronomers 1953–1956

Papers Published	Number of Astronomers
1	88
2	22
3	23
4	20
5	16
6	11
7	1
8	8
9 or more	14

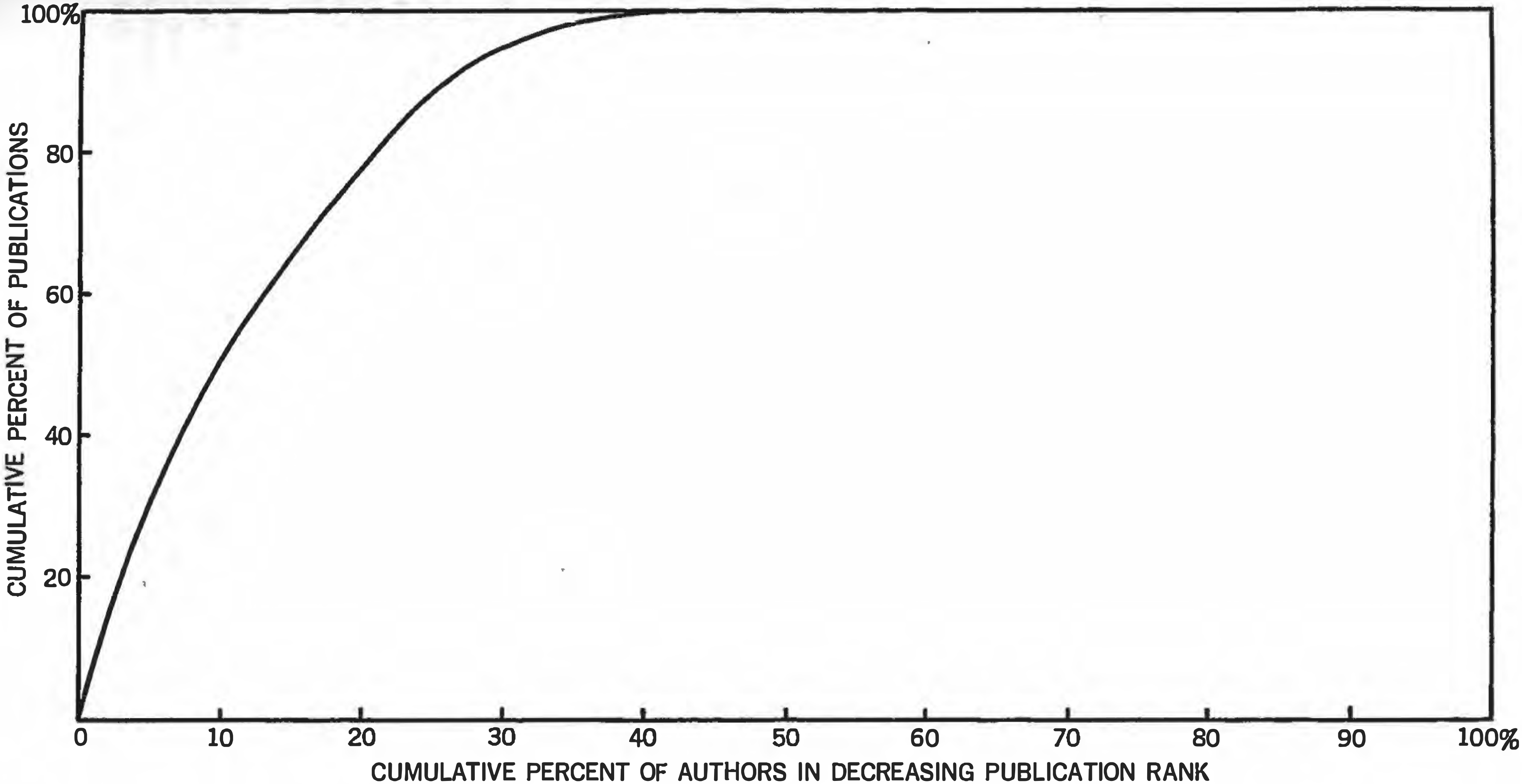


FIGURE C-15
PUBLICATIONS IN *THE PHYSICAL REVIEW* 1920-1957
BY PHYSICISTS WHO RECEIVED Ph.D. IN 1946

Physicists

Membership in the American Physical Society exceeds 12,000. Estimates of the number of physicists active in the United States range upward from 20,000.

The number of physicists holding Ph.D. degrees can be computed from data collected by the Association of Research Libraries, correcting for mortality rate and retirement age. Figure C-3 presents the number of physicists with Ph.D. degrees active during the years 1936–1956. Physicists aged 68 and over are not included in the total nor those now employed in the United States who received their doctoral degree in foreign universities. American physicists who have switched to other professions or reside abroad have not been subtracted.

Any extrapolation of the curve in Figure C-3 is subject to large uncertainties. If the number of degrees granted each year were to remain at the present level — and it probably will not — the total number of Ph.D. physicists would level off in twenty to thirty years at 20,000. If instead one were to extrapolate the rate of increase in the number of Ph.D.'s awarded annually and assume that physicists would continue to represent 20% of all physical scientists, and physical scientists 30% of all doctoral degrees granted, then the figure of 20,000 physicists would be reached before 1970.

before 1970 . . .
20,000 *physicists*

Research Activity — Physicists

The National Scientific Register, under sponsorship of the National Science Foundation, has collected detailed information on the activities and background of trained scientific workers. We have examined the data cards for all physicists with a doctoral degree. The 5202 physicists employed full-time are distributed by employment as shown in Table C-X.

TABLE C-X

Employment of Ph.D. Physicists — National Scientific Register

Type of Employer	No. of Physicists	Percent of Total
Educational and Non-Profit Institutions	2838	54.5
Government	523	10.1
Industry	1770	34.0
Other	71	1.4
	5202	100.0

The primary employment function of each physicist as reported by the National Science Foundation is shown in Table C-XI. Of all physicists reporting, 50.4% classify themselves primarily as researchers, 23.0% as teachers, and the remainder as engaged in other pursuits which are not strictly scientific in nature.

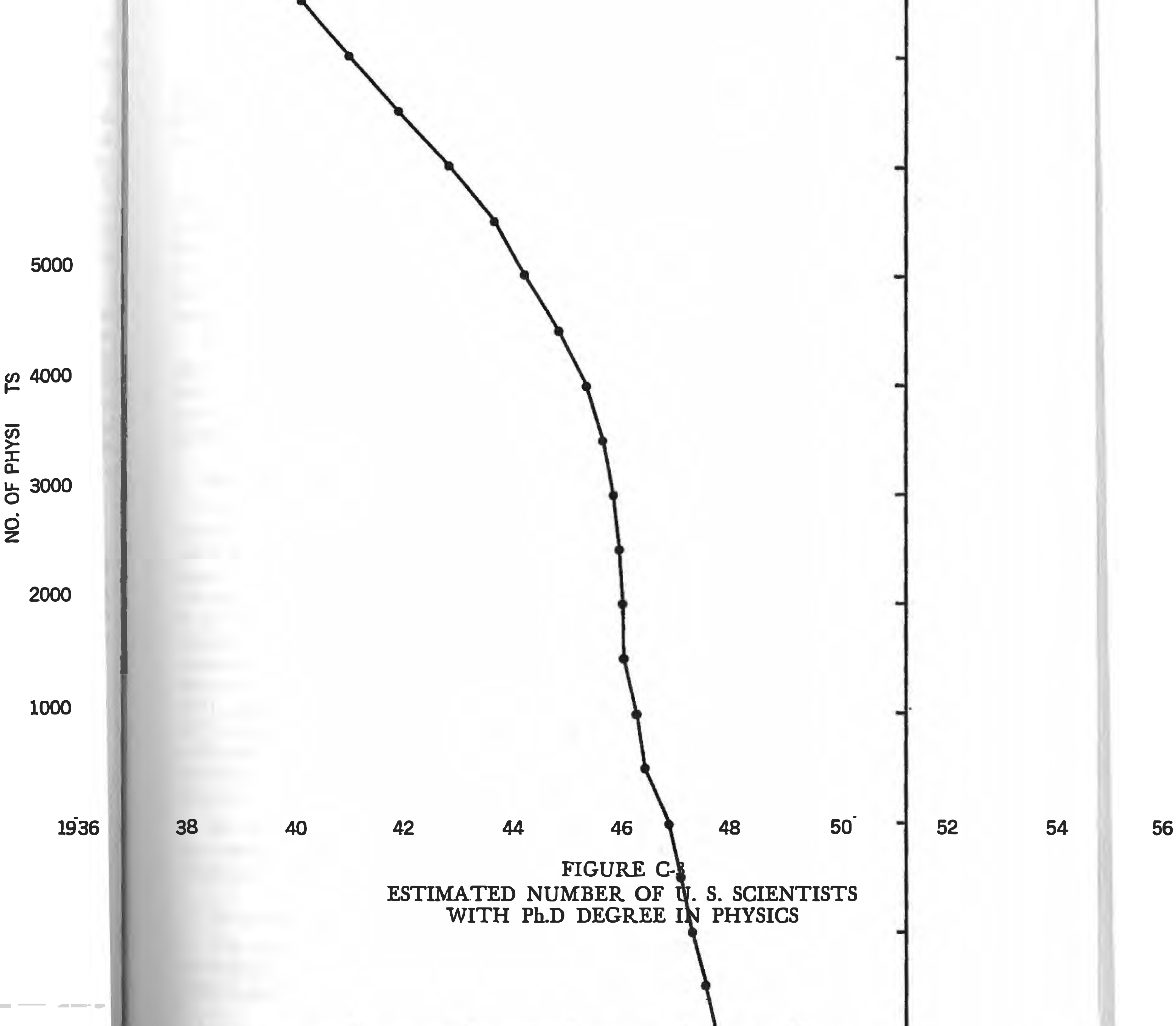


FIGURE C-3
ESTIMATED NUMBER OF U. S. SCIENTISTS
WITH Ph.D DEGREE IN PHYSICS

TABLE C-XI

Primary Employment Function

	Research	Development	Teaching	Management or Administrative	Technical Services
Education	1268	105	1163	249	15
Government	326	13	3	154	22
Industry	969	252	2	472	68

These results are not necessarily objective; they may be influenced by what each scientist wishes he were doing, rather than by what he is actually doing. University professors, for example, may overestimate their research activity; similarly, scientists employed by industry or in Government service may exaggerate their management or administrative duties. The inescapable conclusion is, however, that research, particularly basic research, is not the only activity of trained scientists.

results may be influenced by what the scientist wishes he were doing

For improved reliability of this information, it would be useful to identify and interview each physicist and estimate his present and potential contribution to basic research. This approach could not be pursued within the time limit of our study. Instead we have examined publications as a measure of basic research potential.

Basic Research Publications — Physicists

Scientists engaged in basic research publish their findings in scientific journals. A scientist who has not submitted a research paper to a recognized scientific publication for some years is not likely to be devoting more than a fraction of his time to basic research. We have considered the publication rate of all physicists who obtained their doctoral degree in an American university in 1936, 1941, 1946, and 1951. The frequency distribution of their most recent publication in *The Physical Review*, the journal where most fundamental discoveries in physics are reported, is shown in Figures C-4 through C-7. The figures show that 47% of all 1951 graduates have published in *The Physical Review* in the last five years, 30% of the 1946 graduates, 18% of the 1941 graduates, and 15% of the 1936 graduates. The decrease of publication rate with age can be explained by the assumption that recent graduates are strongly research-minded; in time many will drift away from basic research.

recent graduates are strongly research-minded

We conclude that 20–30% of the physicists holding Ph.D. degrees are active in basic research and contribute to the scientific literature. Their individual contributions vary greatly.

Relation Between Publication Rate and Scientific Competence

The most widely accepted measure of the scientific competence of an individual is the one agreed upon by colleagues acquainted with his achievements and his working habits. These opinions may not always

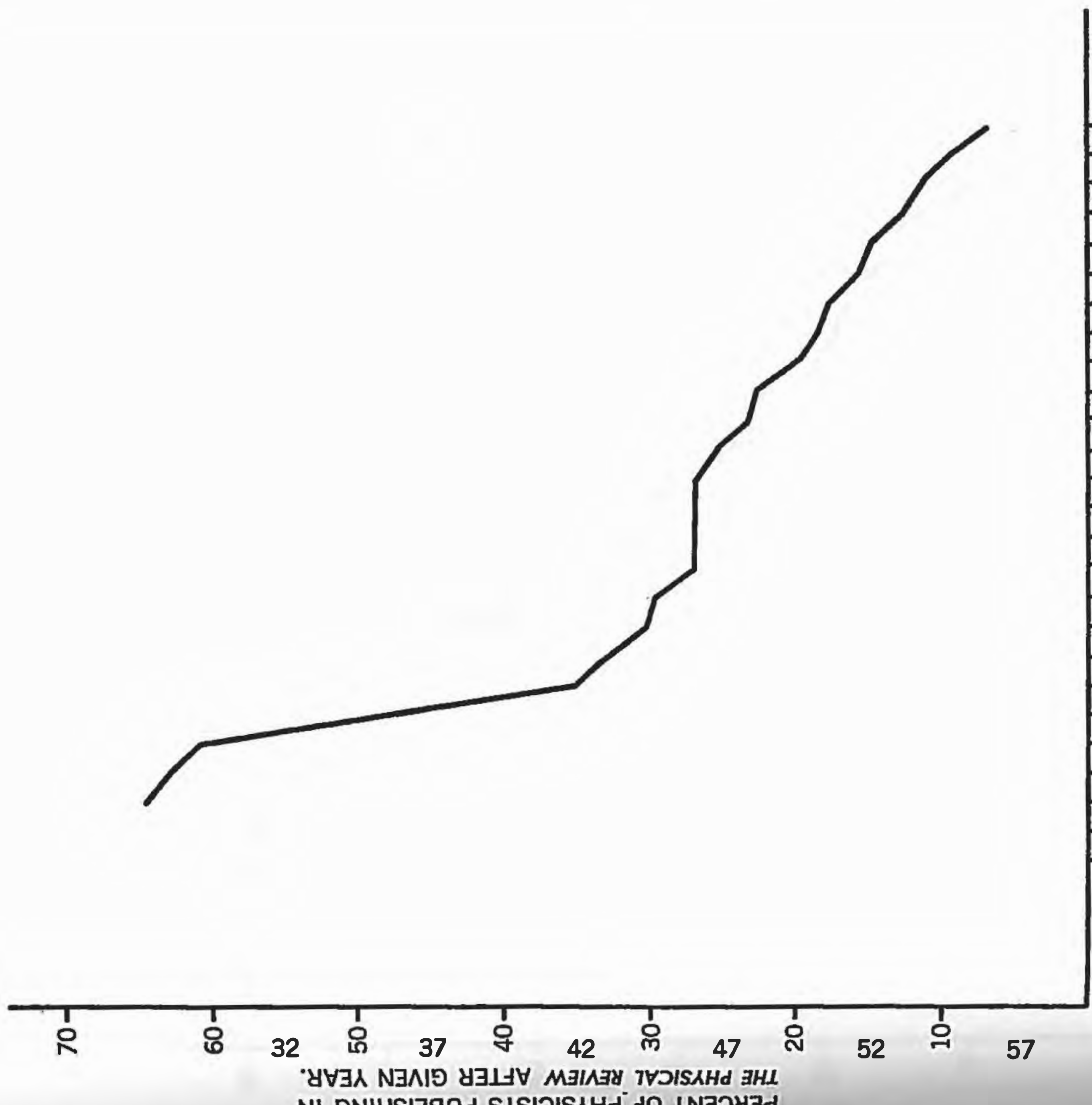


FIGURE C-4
PHYSICISTS (Ph.D. 1936)
PHYSICISTS ACTIVE IN BASIC RESEARCH
AS MEASURED BY PUBLICATIONS IN
THE PHYSICAL REVIEW.

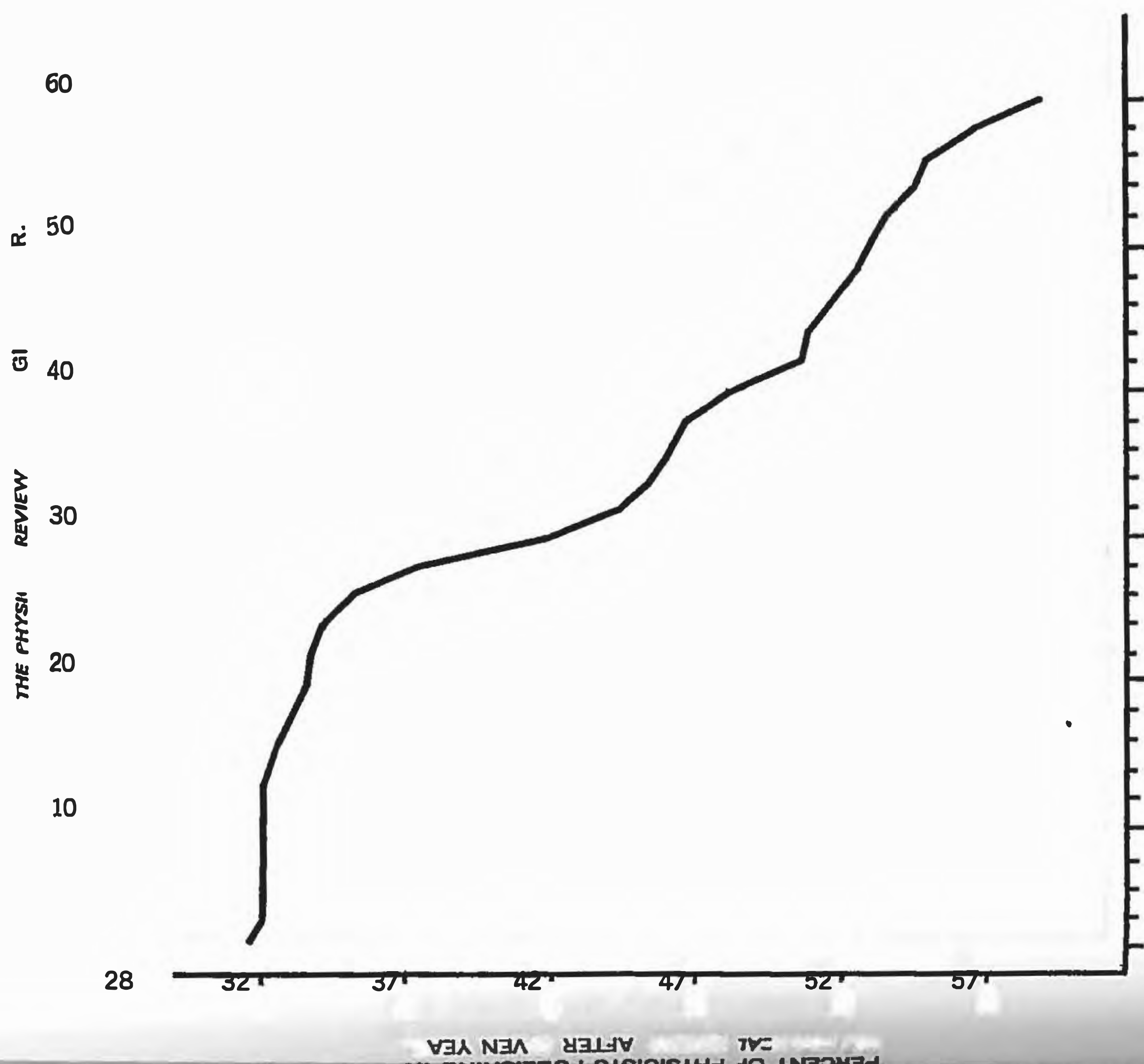


FIGURE C-5
PHYSICISTS (Ph.D. 1941)
PHYSICISTS ACTIVE IN BASIC RESEARCH
AS MEASURED BY PUBLICATIONS IN
THE PHYSICAL REVIEW.

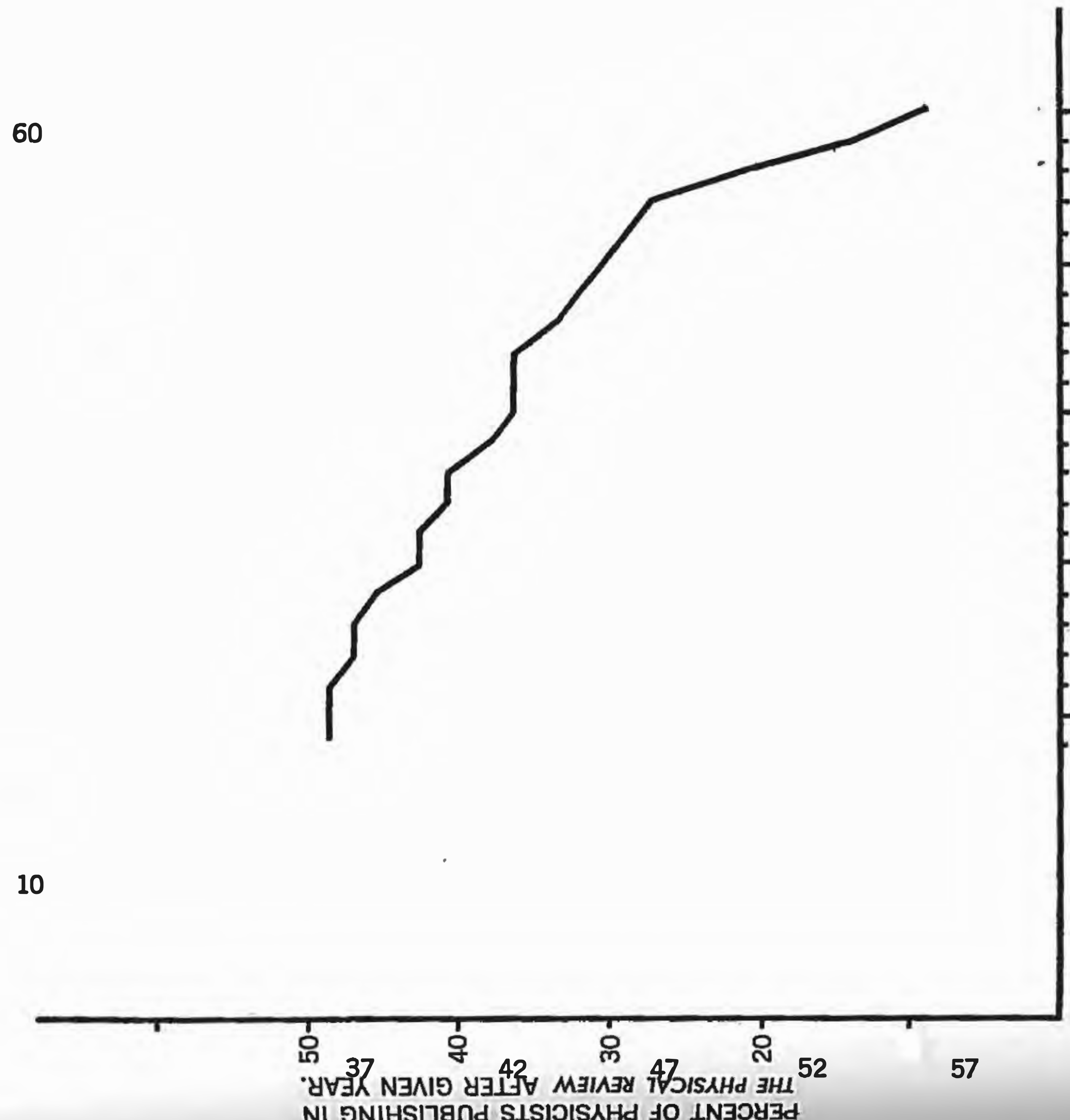


FIGURE C-6
PHYSICISTS (Ph.D. 1946)
PHYSICISTS ACTIVE IN BASIC RESEARCH
AS MEASURED BY PUBLICATIONS IN
THE PHYSICAL REVIEW

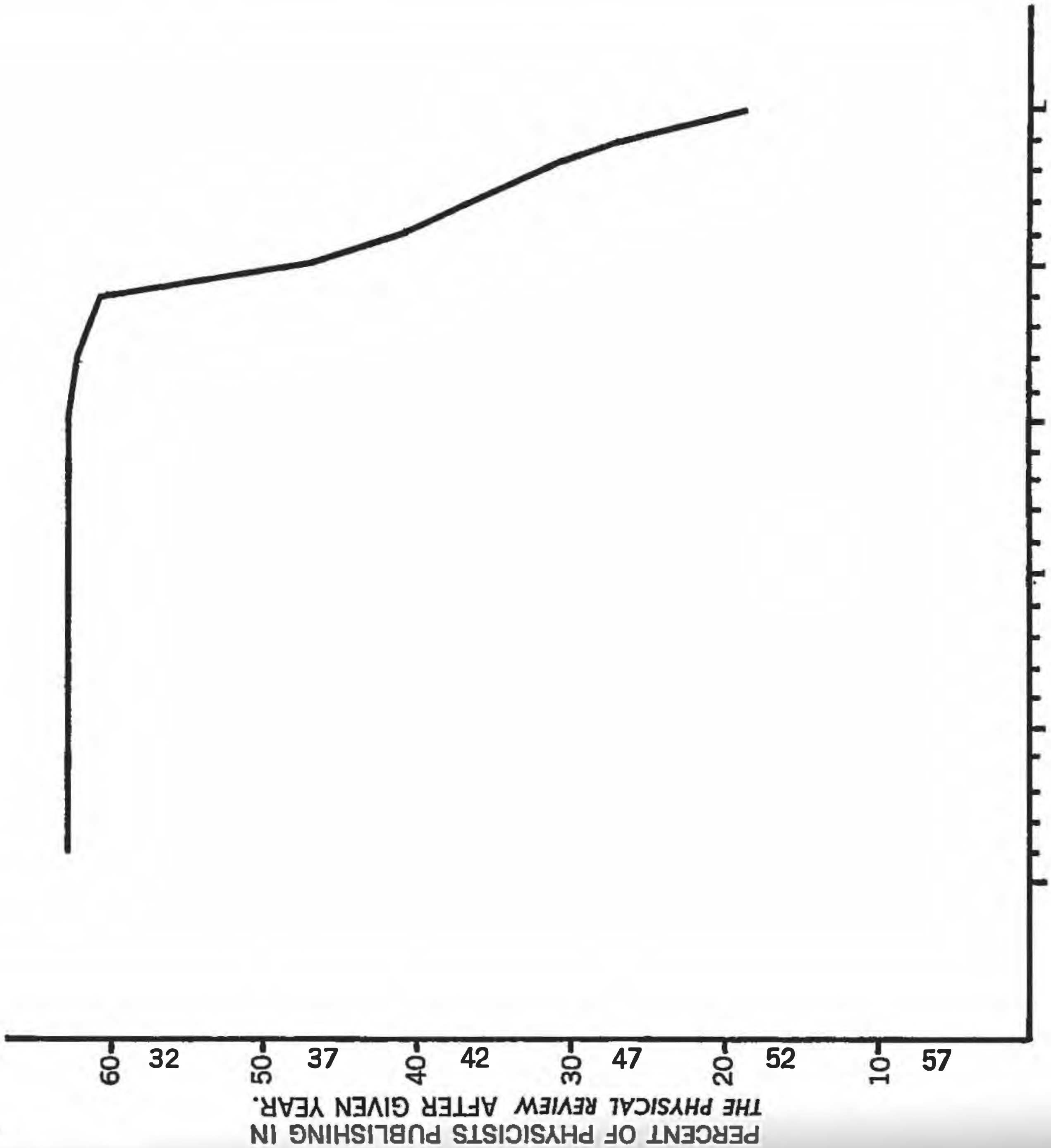


FIGURE C-7
PHYSICISTS (Ph.D. 1951)
PHYSICISTS ACTIVE IN BASIC RESEARCH
AS MEASURED BY PUBLICATIONS IN
THE PHYSICAL REVIEW

be unanimous and may at times prove erroneous; in general, however, they are reliable. Promotions, salary levels, and scientific recognition ultimately rest on these personal judgments. We have not had the opportunity to conduct opinion surveys among scientists and have relied instead on comparable ratings. The Institute of Physics, for example, elects some of its members to fellowship. The criteria for this selection are not clearly expressed in the by-laws of the Society. They are based on scientific competence as understood within the scientific community. Election to the National Academy of Science is a significant honor bestowed for outstanding scientific achievements.

We have examined publication rates in *The Physical Review* of fellows of the Institute of Physics, members of the Academy of Science, and other physicists. The sample analyzed consists of all physicists who obtained their Ph.D. degree in 1936, 1941, 1946, and 1951. Figures C-8 through C-12 are histograms of the average number of publications of fellows of the Institute of Physics and of non-fellows. The number of publications by members of the Academy of Science of the Class of 1936 is shown separately. Too few of the younger men (Classes of 1941, 1946, and 1951) are members of the Academy to justify presenting comparable graphs for later years.

striking difference in the publication rate of fellows and of non-fellows

There is a striking difference in the publication rate of fellows and of non-fellows for every one of the four graduating classes considered. The very high publication rate of the Class of 1951 is due, in part, to the fact that many potential fellows have not yet been elected by the Society. Their inclusion within the non-fellow group tends to raise the average publication rate of fellows (only very outstanding young men belong to this group) and of non-fellows (this group includes men who will soon be advanced to fellowship). Figure C-12 shows that members of the Academy of Science have an even higher publication rate. They publish almost twice as many papers as fellows of the Institute of Physics. These results — that "publication rate" is strongly correlated with scientific recognition — are in agreement with the findings reported by Shockley[7] Dennis[8], and Fisher[9]. Similar results were obtained from the study of astronomers: the publication rate of members of the National Academy of Science is four times higher than the publication rate of other astronomers.

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[7] William Shockley, "On the Statistics of Individual Variations of Productivity in Research Laboratories," Proceedings of the IRE, Vol. 45, pp. 279–290; March, 1957.

[8] Wayne Dennis, "Bibliography of Eminent Scientists," Scientific Monthly, Vol. 79, pp. 180–183; September, 1954.

[9] J. C. Fisher, "Who Does Basic Research in Industry," General Electric Research Laboratory, Schenectady, New York; private communication.

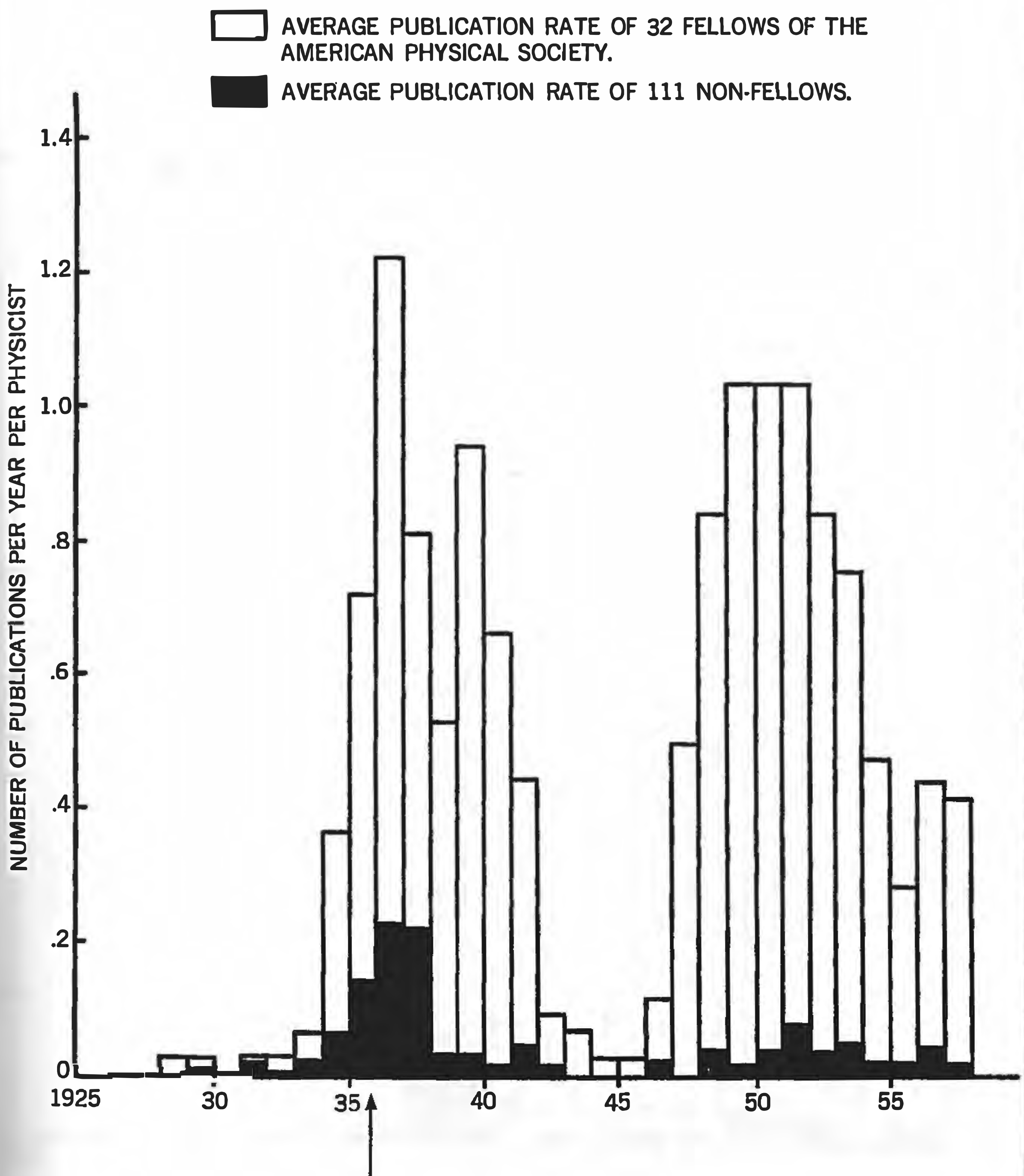


FIGURE C-8
PUBLICATION RATE IN *THE PHYSICAL REVIEW*
OF PHYSICISTS WHO OBTAINED Ph.D. IN 1936

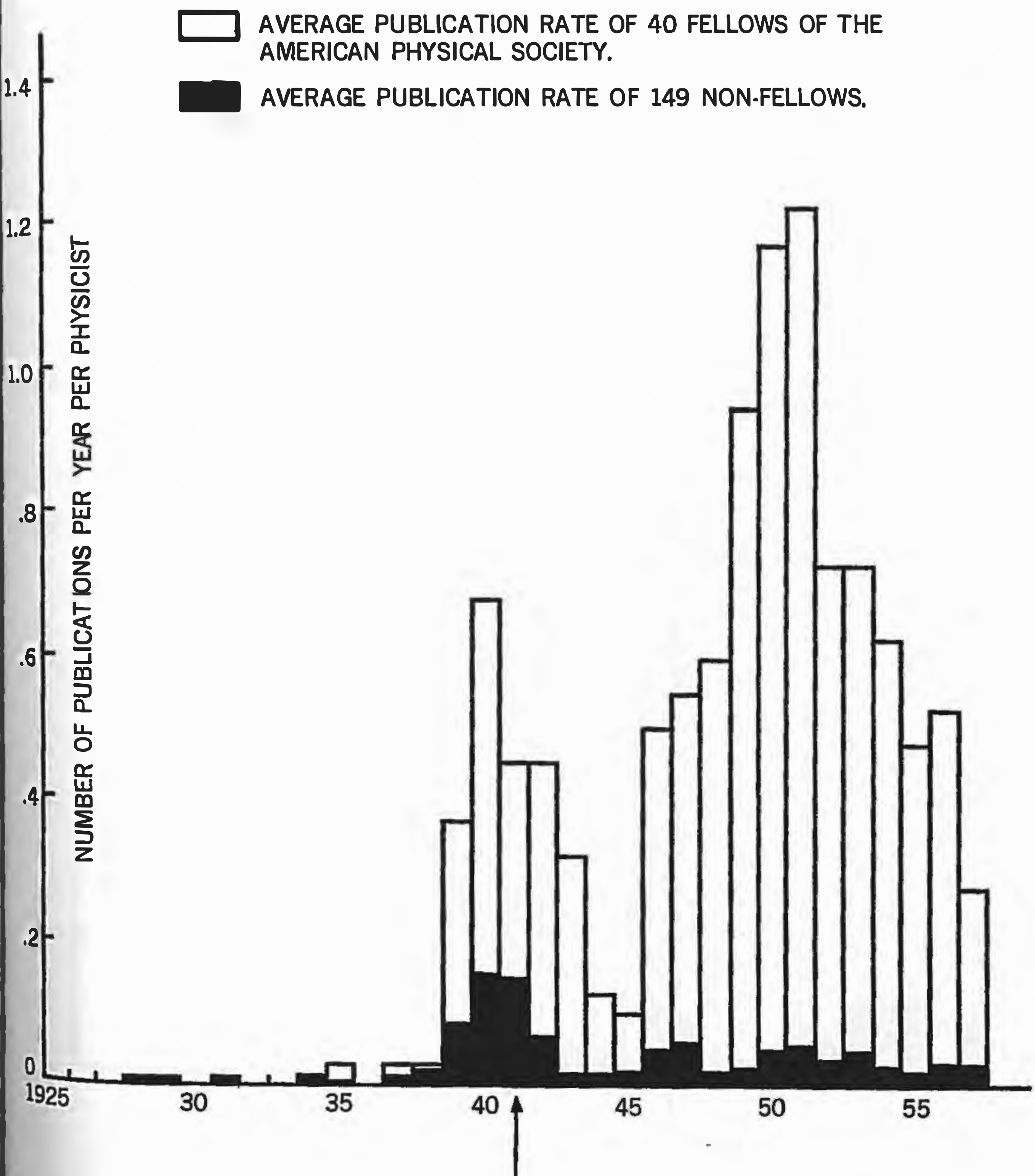


FIGURE C-9
PUBLICATION RATE IN *THE PHYSICAL REVIEW*
OF PHYSICISTS WHO OBTAINED Ph.D. IN 1941

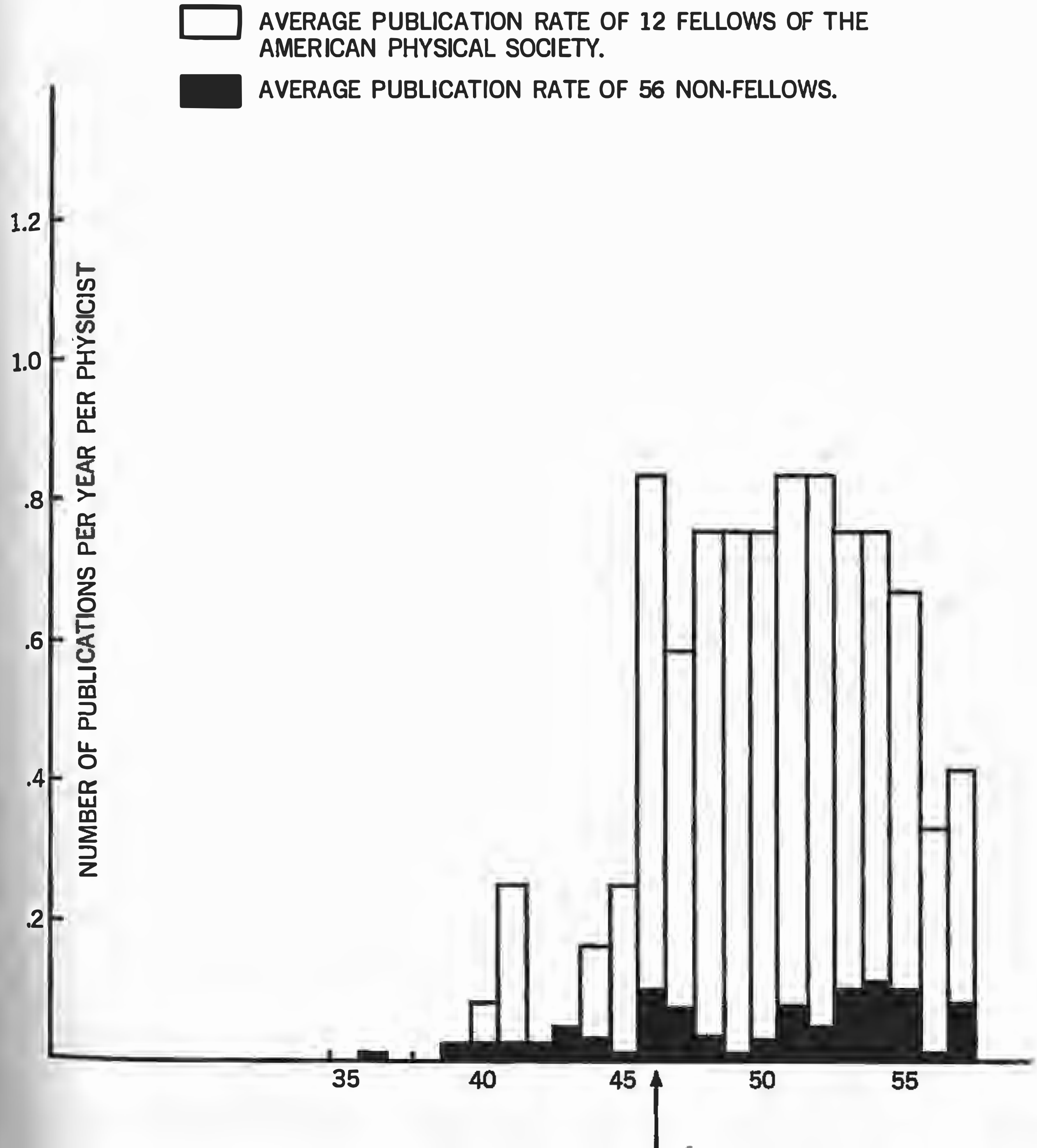


FIGURE C-10
PUBLICATION RATE IN *THE PHYSICAL REVIEW*
OF PHYSICISTS WHO OBTAINED Ph.D. IN 1946

We conclude that publication rate is a useful measure of scientific attainments. Corroborative evidence has been obtained by correlating publication rate with:

Receipt of research grants

Academic rank

Salary level

Number of graduate students supervised.

publication rate is one index of individual competence

We do not mean to imply that routine ranking devices such as publications can provide reliable indices of the competence of an individual. The factors determining research effectiveness are too numerous and their significance is little understood. Our object is to estimate how many scientists contribute most of the basic research results, not to develop an absolute scale for ranking individual scientists.

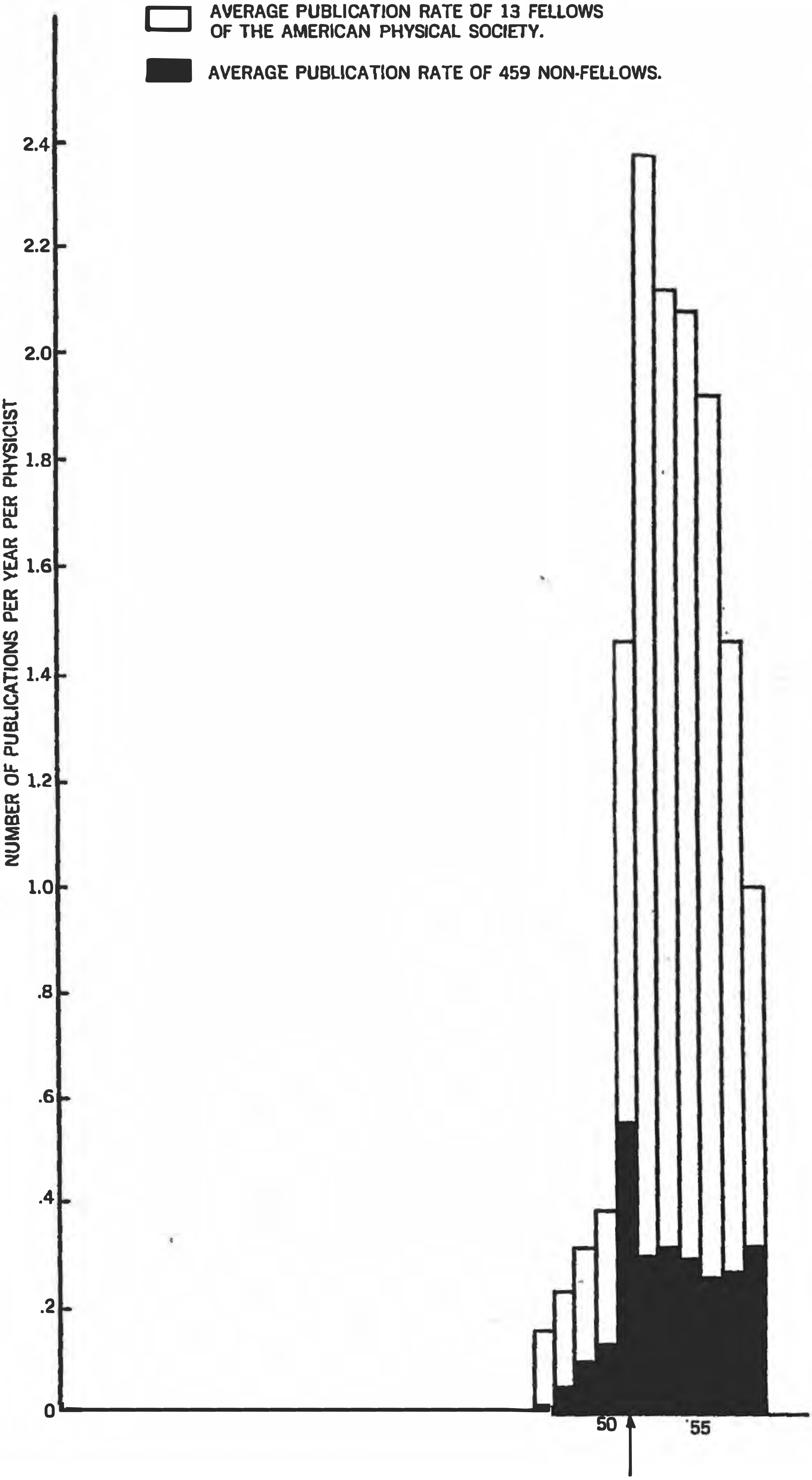
Figures C-13 through C-16 show the cumulative percent of publications in *The Physical Review* plotted against the cumulative percent of authors ranked in decreasing order of their rate of publication. Figure C-13, for example, refers to the graduating class of 1936. Of the 143 members of this class, 20% have contributed 80% of all the publications appearing in *The Physical Review* from 1920 to 1957.

Since many science students abandon basic research after completing their academic work, and all their scientific publications derive directly from their dissertation, we have also included graphs similar to the ones in Figures C-13 through C-16, but with papers published during the first three years following graduation subtracted. We now find that 10% of the 1936 graduating class accounts for 80% of all publications contributed by this class appearing in *The Physical Review* from 1939 to 1957 (Figures C-17 through C-20).

Chemists

The American Chemical Society publishes annually a *Directory of Graduate Research*, which lists publications and biographical information about faculty members in universities with graduate schools in chemistry, chemical engineering, and biochemistry. Figure C-21 shows the age distribution of chemistry faculty members as related to academic rank; Figure C-22 the percentage of all faculty members who published five or more scientific papers in the years 1954–1956, plotted against age.

Together, these graphs suggest that the rate of publication of chemists on university staffs is not seriously affected by age or attainment of tenure ranks. The apparently lower publication rate of younger men is explained by the fact that their scientific productivity does not span the full three-year period for which publications are reported.


AVERAGE PUBLICATION RATE OF 13 FELLOWS OF THE AMERICAN PHYSICAL SOCIETY.
AVERAGE PUBLICATION RATE OF 459 NON-FELLOWS.
NUMBER OF PUBLICATIONS PER YEAR PER PHYSICIST
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
50
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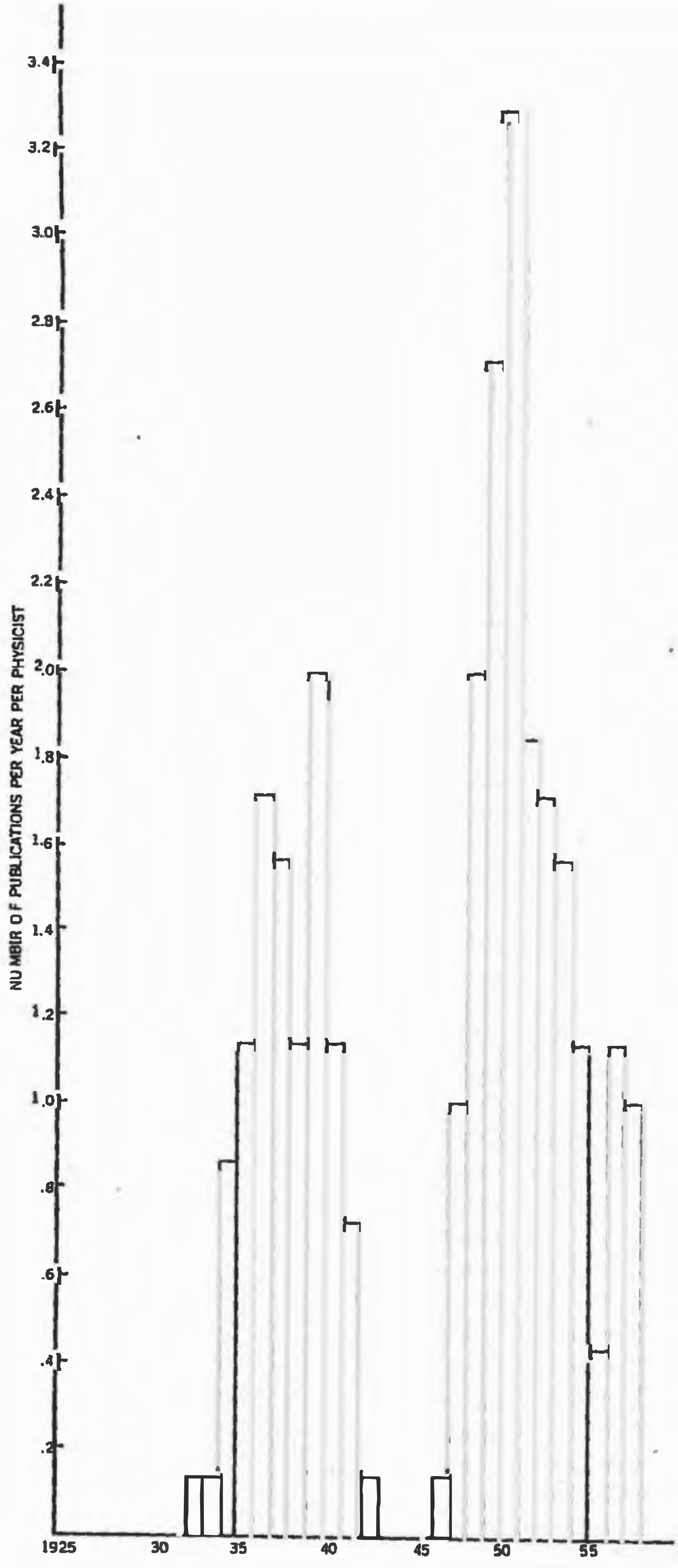

FIGURE C-12
PUBLICATION RATE OF 7 PHYSICISTS WHO
OBTAINED Ph.D. IN 1936 AND ARE NOW MEMBERS
OF THE NATIONAL ACADEMY OF SCIENCE

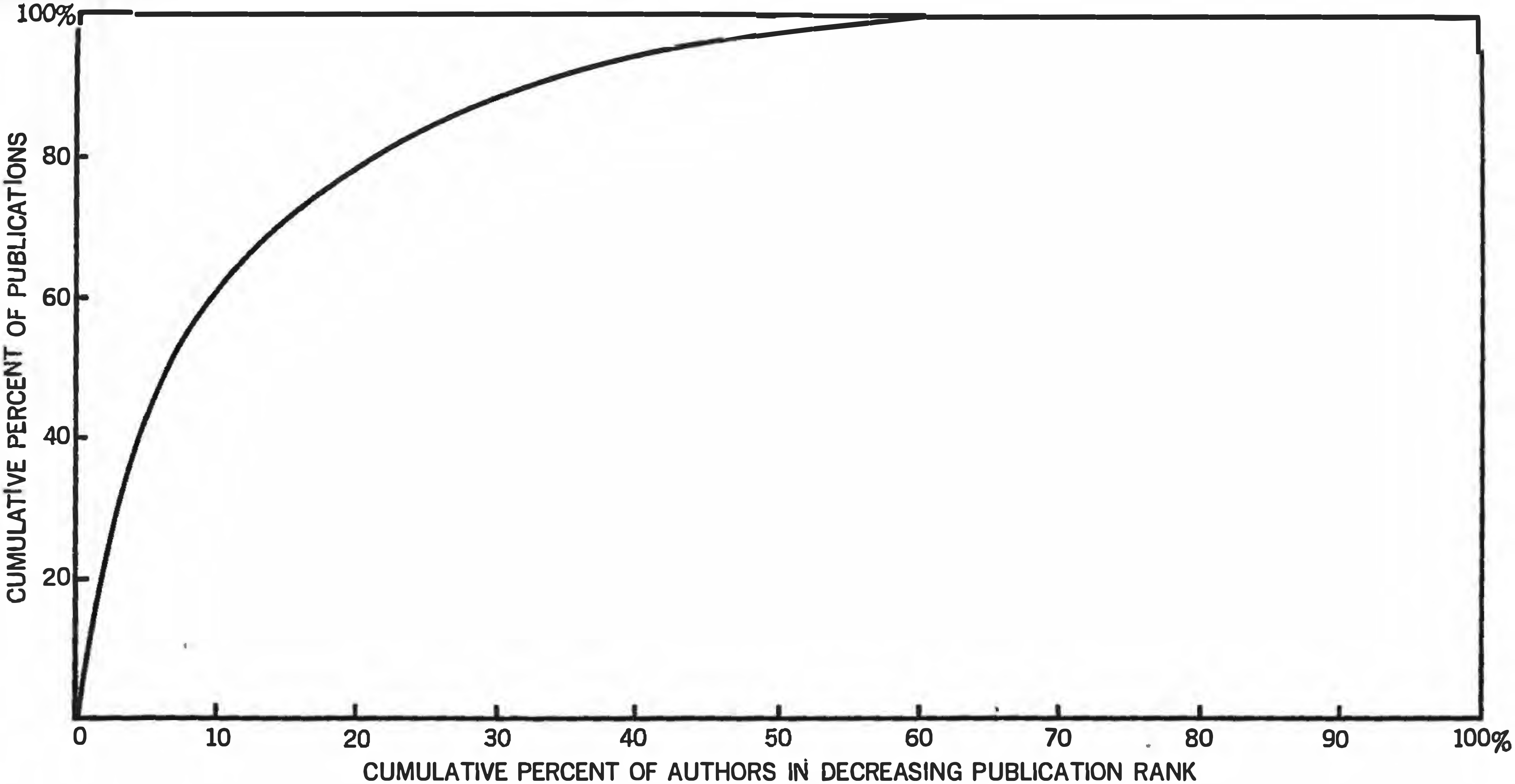

FIGURE C-13
PUBLICATIONS IN *THE PHYSICAL REVIEW* 1920-1957
BY PHYSICISTS WHO RECEIVED Ph.D. IN 1936

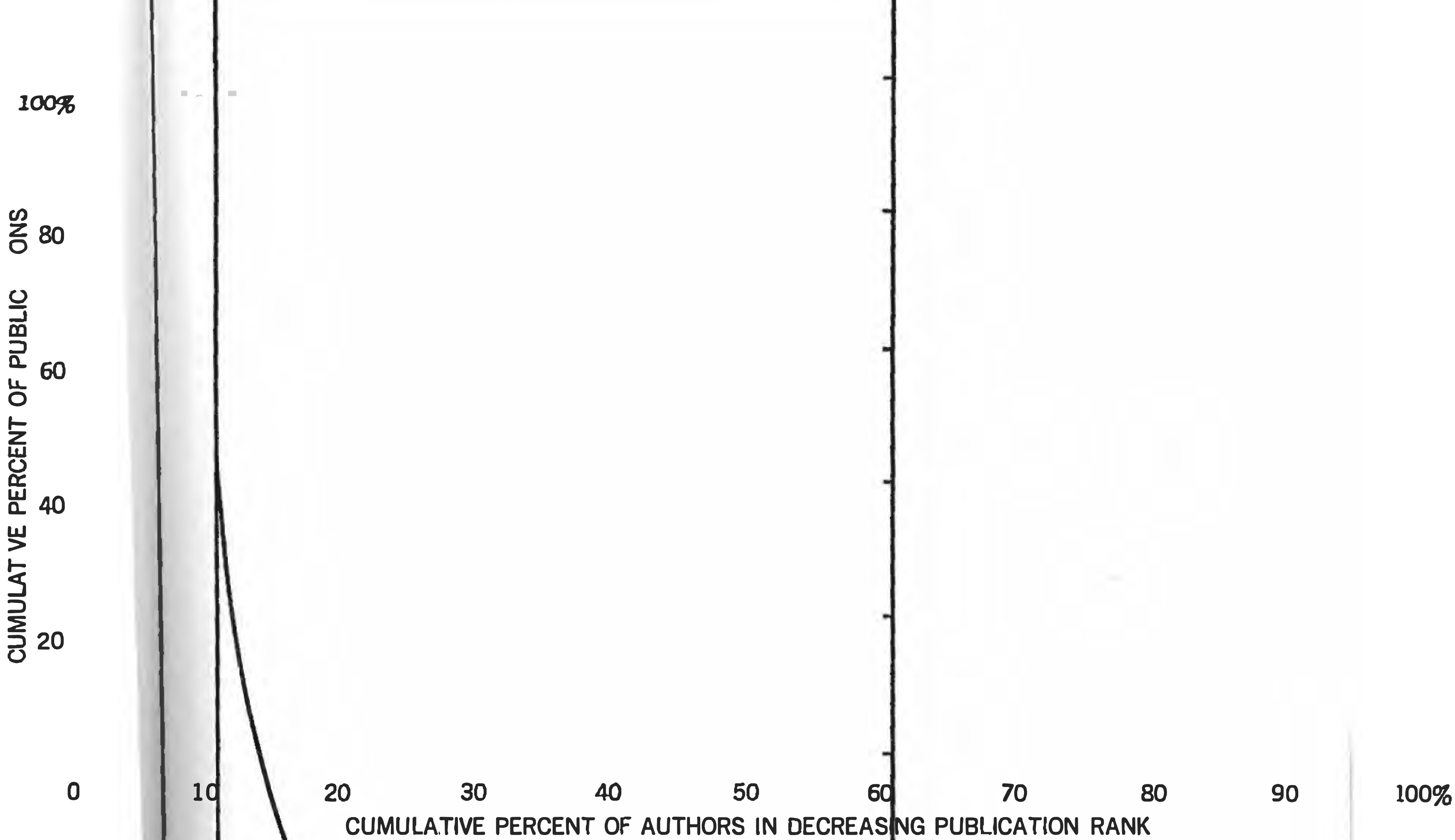

FIGURE C-14
PUBLICATIONS IN *THE PHYSICAL REVIEW* 1920-1957
BY PHYSICISTS WHO RECEIVED Ph.D. IN 1941

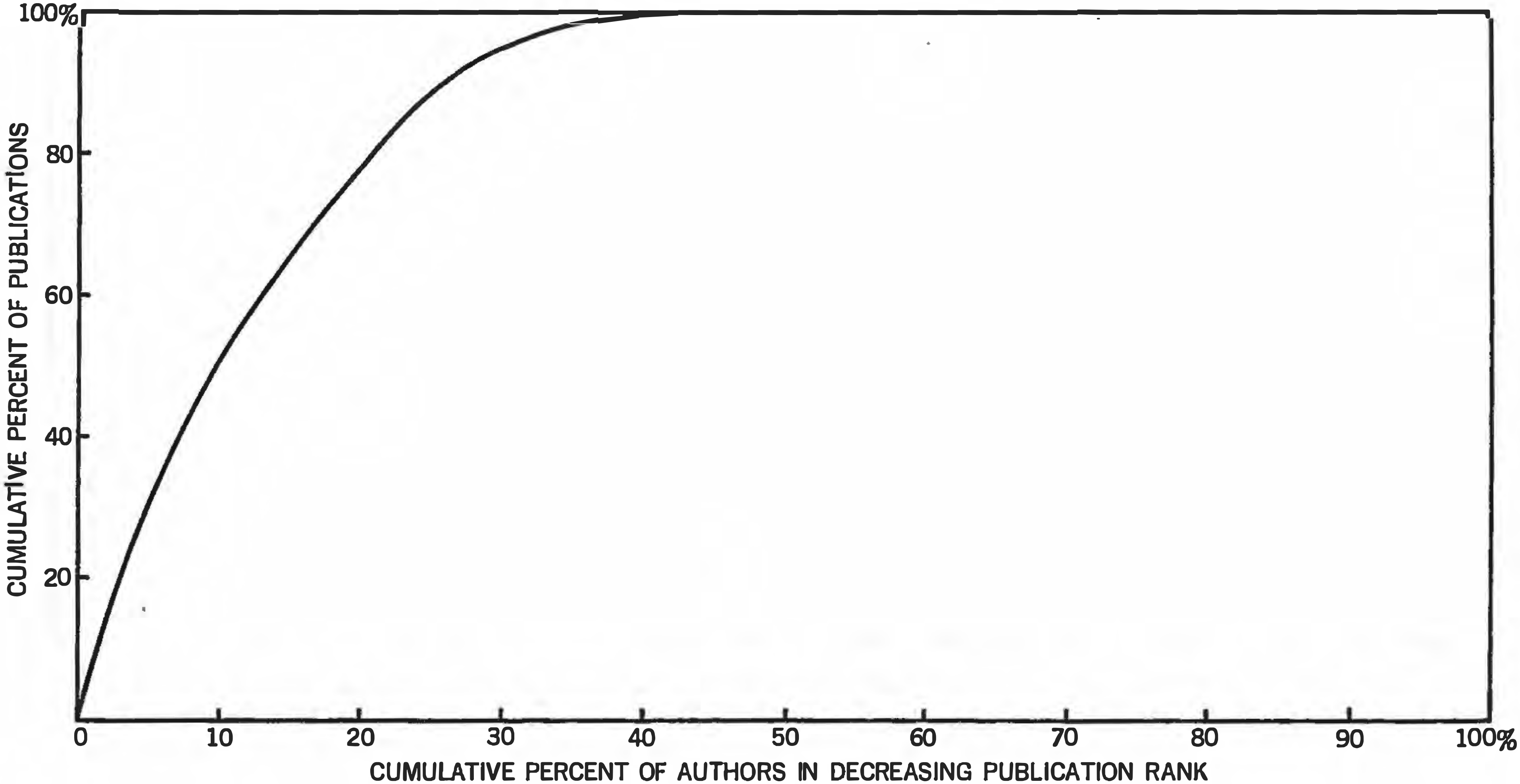

FIGURE C-15
PUBLICATIONS IN *THE PHYSICAL REVIEW* 1920-1957
BY PHYSICISTS WHO RECEIVED Ph.D. IN 1946

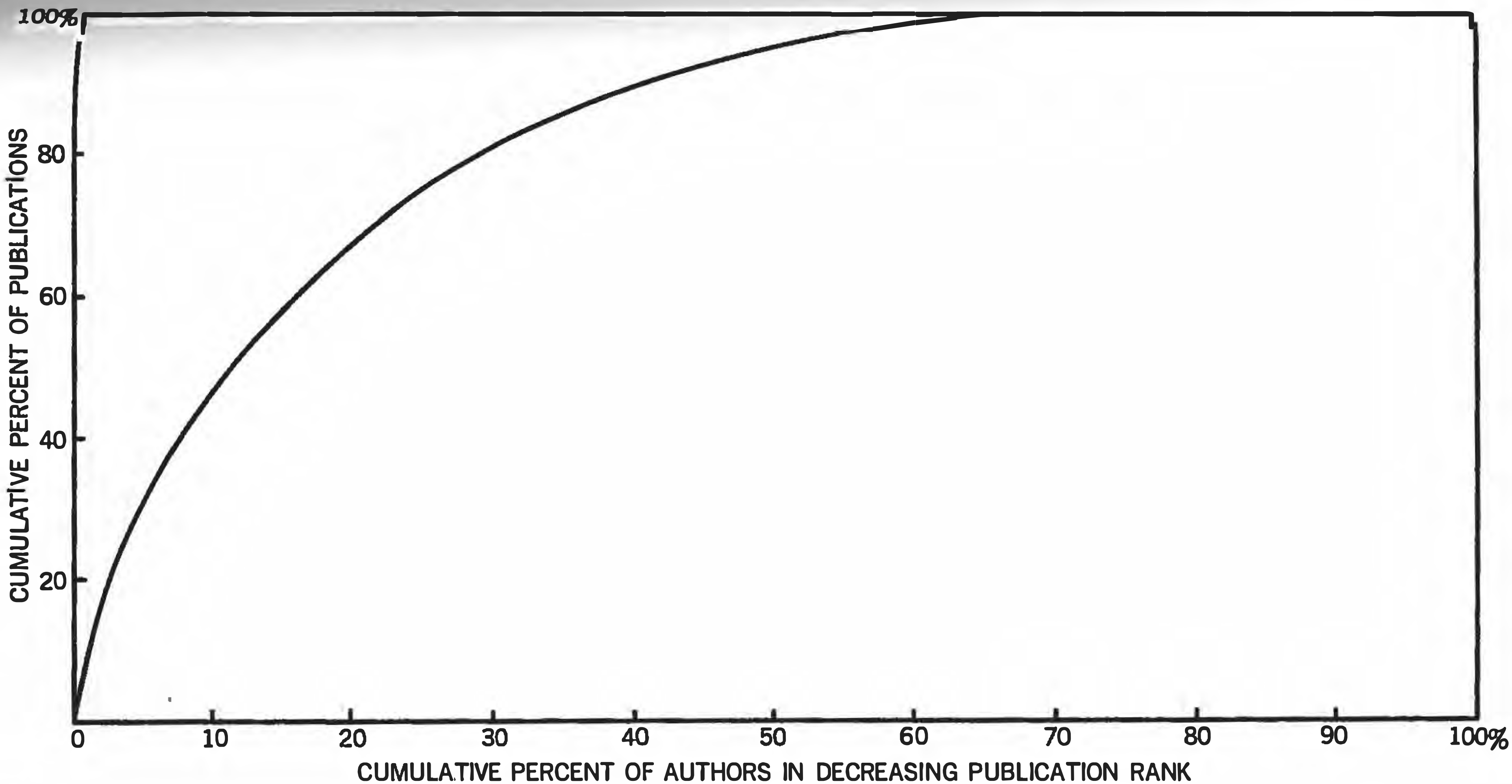

FIGURE C-16
PUBLICATIONS IN *THE PHYSICAL REVIEW* 1920-1957
BY PHYSICISTS WHO RECEIVED Ph.D. IN 1951

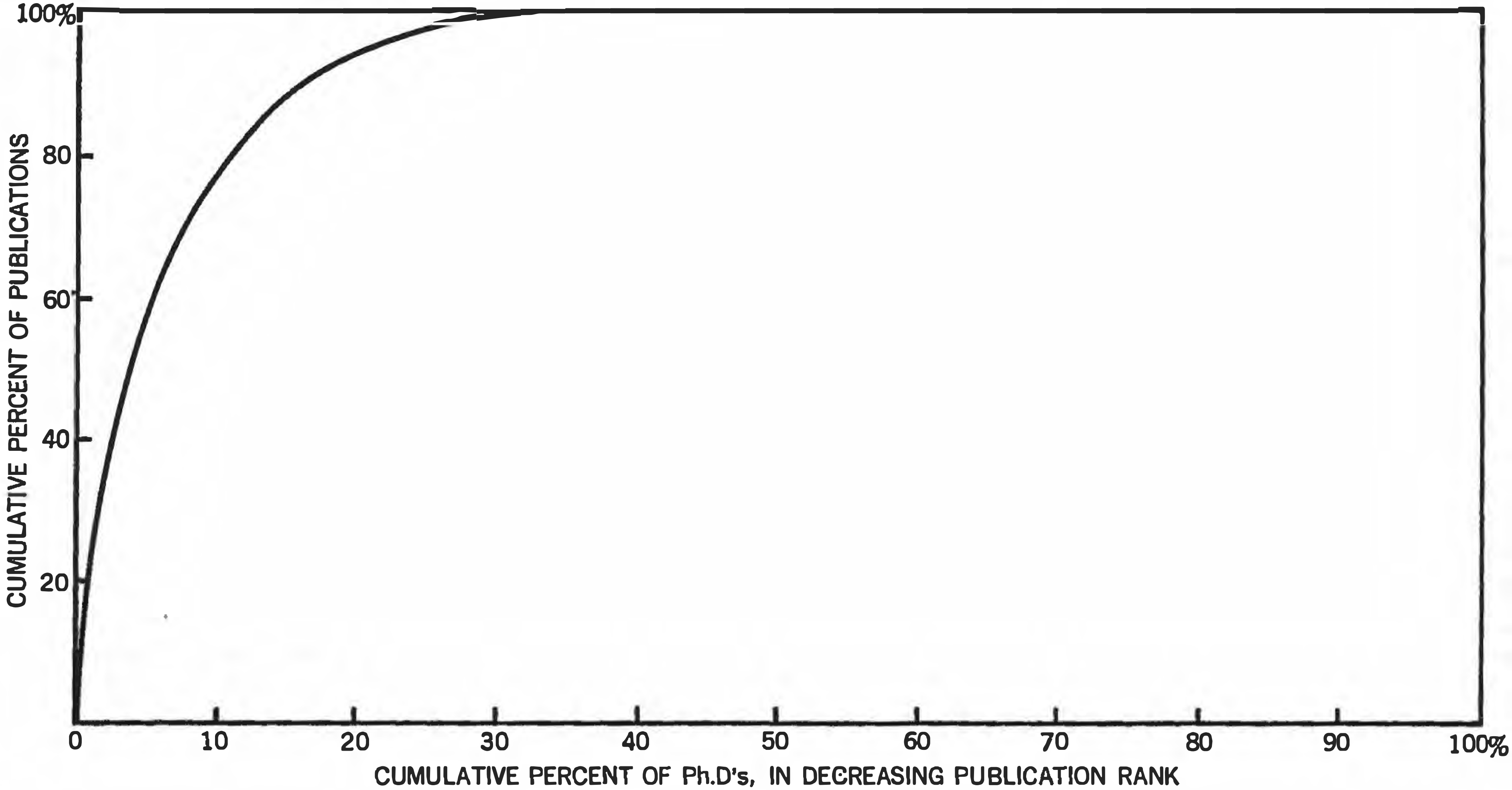

FIGURE C-17
PUBLICATIONS IN *THE PHYSICAL REVIEW* 1939-1957
BY PHYSICISTS WHO RECEIVED Ph.D. IN 1936
(first three years after degree removed)

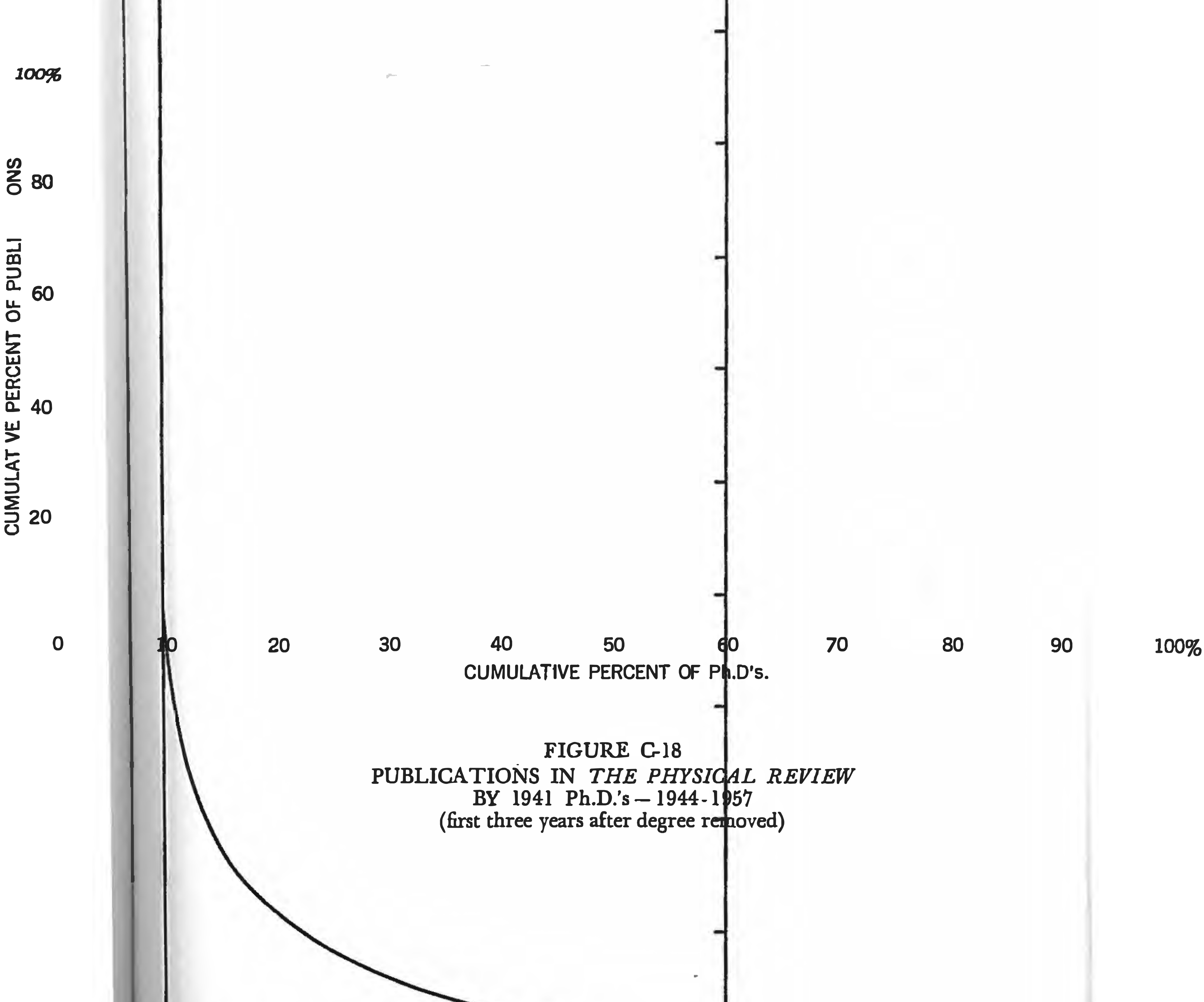

FIGURE C-18
PUBLICATIONS IN *THE PHYSICAL REVIEW*
BY 1941 Ph.D.'s — 1944-1957
(first three years after degree removed)

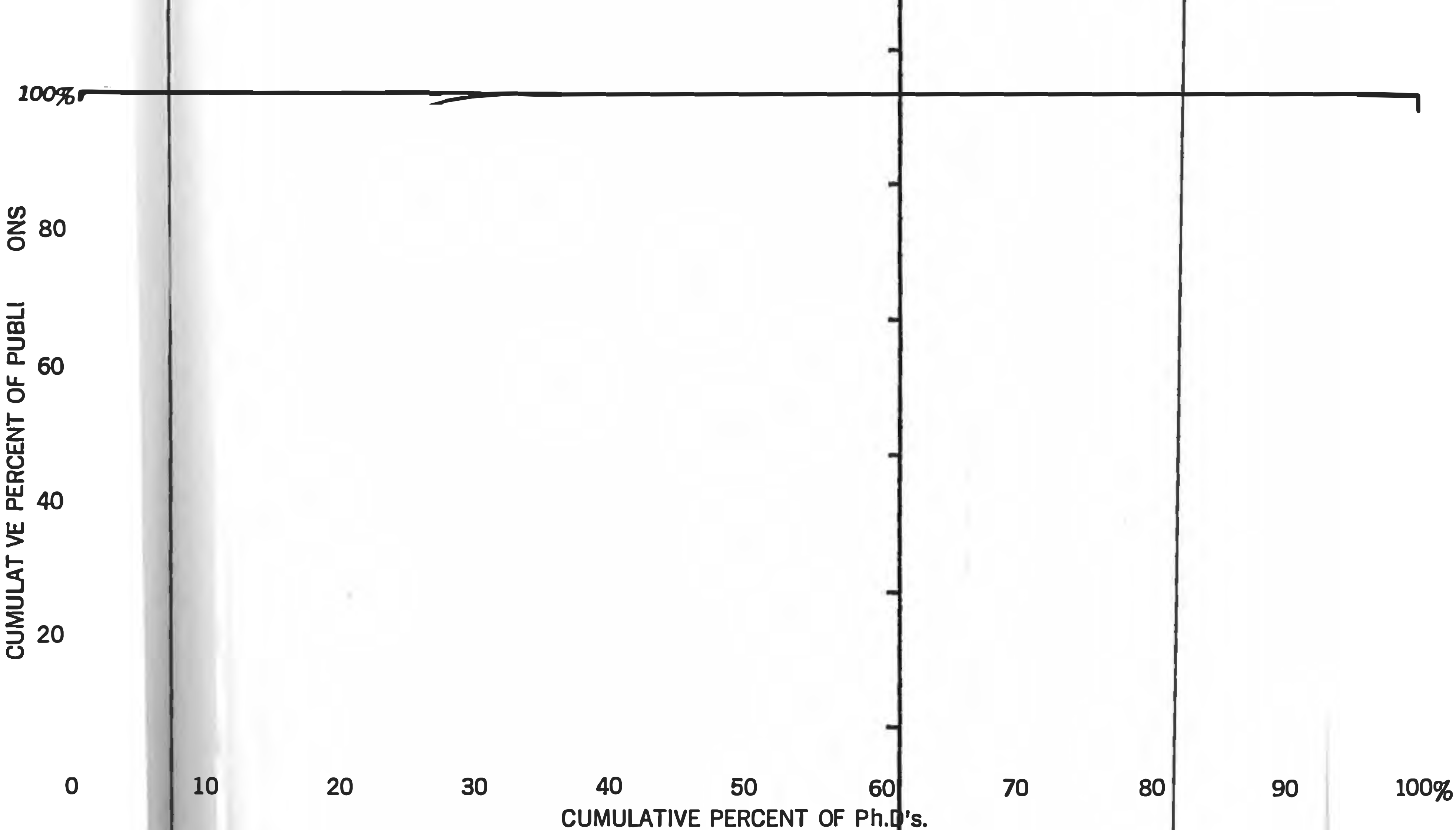

FIGURE C-19
PUBLICATIONS IN *THE PHYSICAL REVIEW*
BY 1946 Ph.D.'s — 1949 - 1957
(first three years after degree removed)

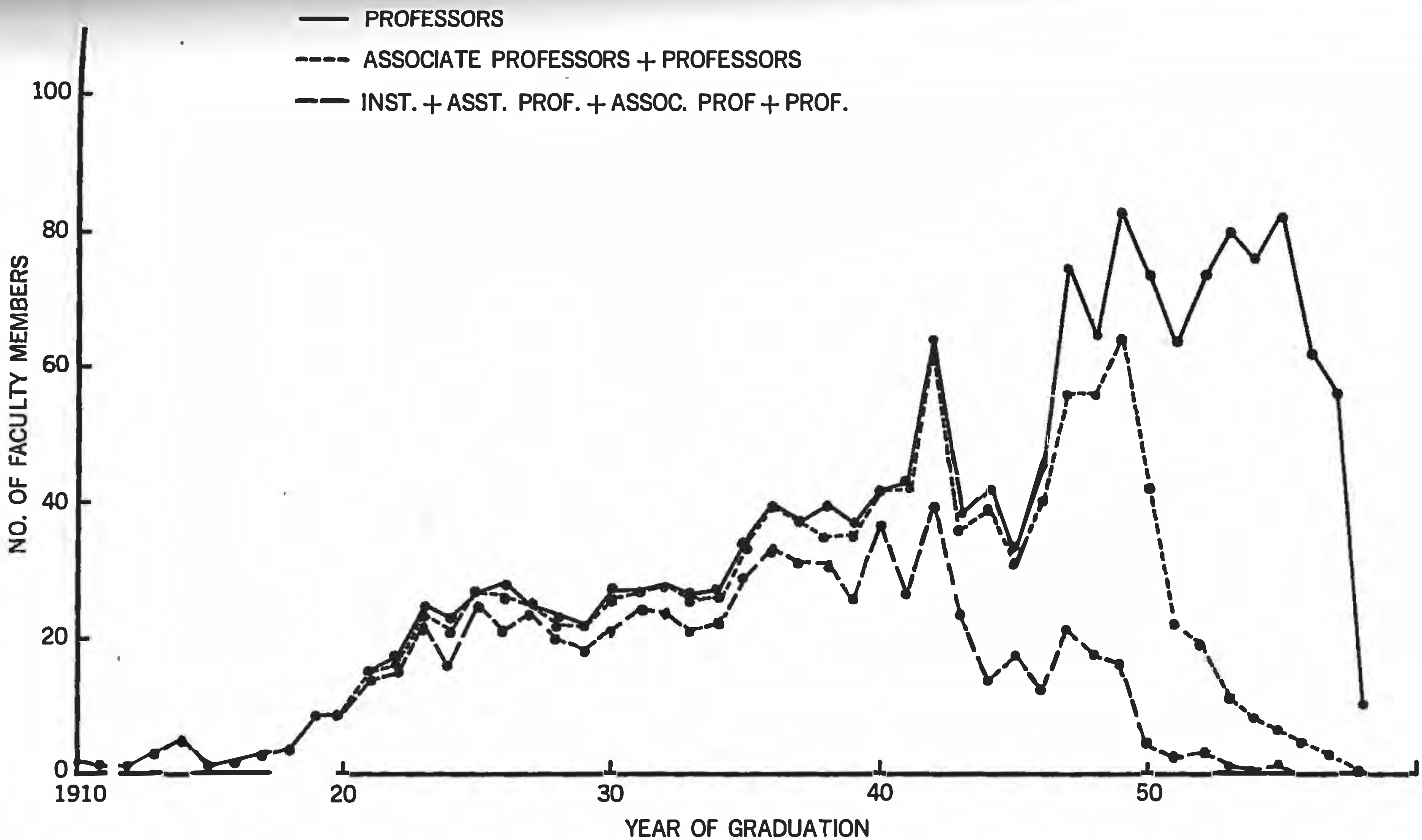

FIGURE C-21
UNIVERSITY FACULTY MEMBERS (CHEMISTRY DEPARTMENTS) YEAR OF GRADUATION (Ph.D.) AND PRESENT ACADEMIC RANK

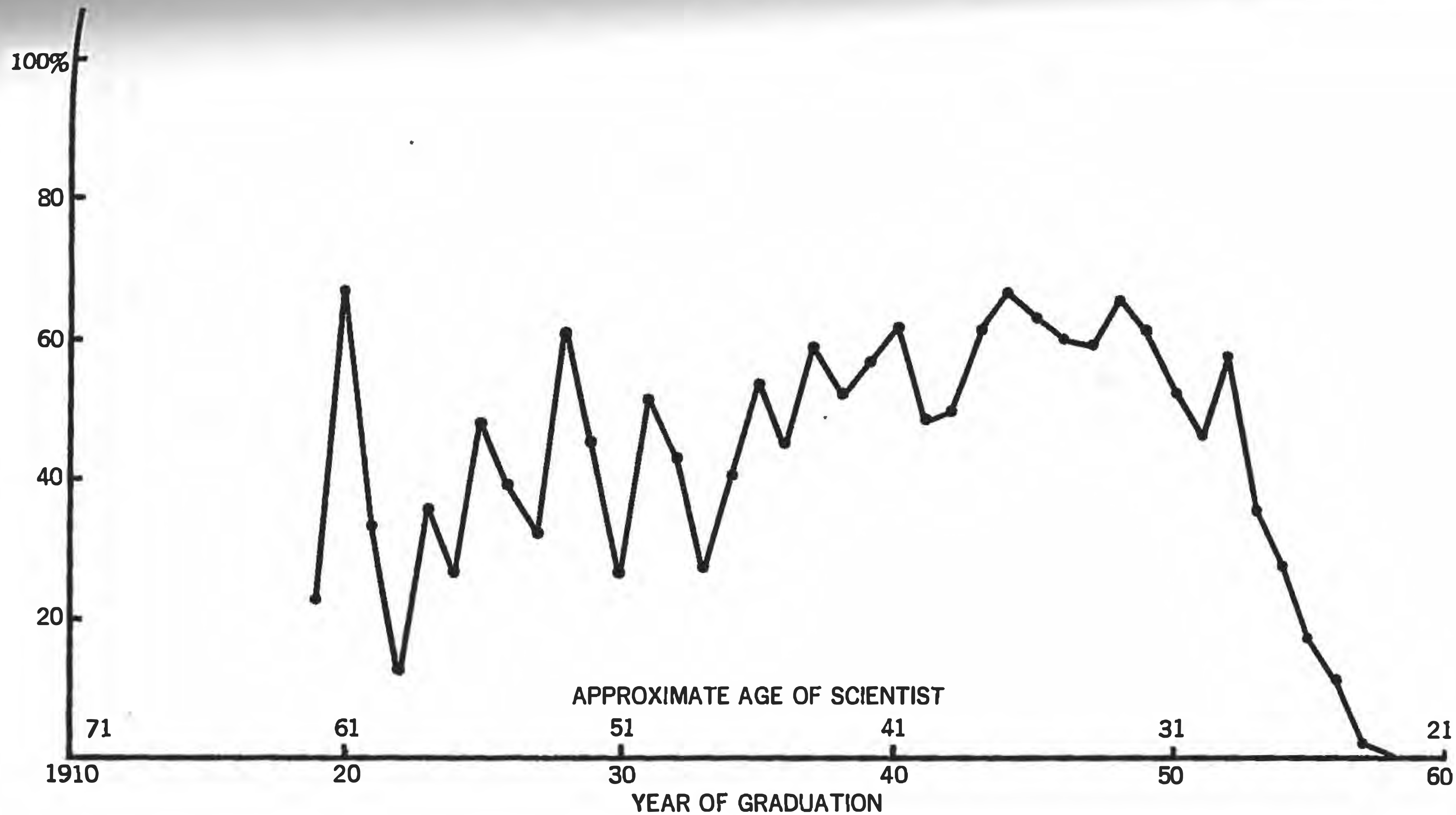

FIGURE C-22
PUBLICATION RATE AS FUNCTION OF AGE
UNIVERSITY FACULTY MEMBERS (CHEMISTRY DEPARTMENTS) PERCENT PUBLISHING 5 OR MORE PAPERS DURING THE PERIOD 1954-1956, BY YEAR OF GRADUATION (Ph.D.)

The total number of publications of chemists who received a doctorate in 1936 and 1941 was determined from the Author Index of *Chemical Abstracts.* Figures C-23 and C-24 show the average number of publications per chemist per year from 1927 to the present. The contribution of these two classes of chemists to the *Journal of the American Chemical Society* is presented in Figures C-25 and C-26. Approximately 30% of all Ph.D. chemists contribute 80% of the research publications appearing in the *Journal of the American Chemical Society.*

Basic Research — Expenditures, Personnel, Publications

Three measures of research effort have been considered:

- Basic research expenditures
- Number of scientists and engineers engaged in basic research
- Number of scientific publications generated by research institutes.

Table C-XII compares these three independent measures of basic research activity. Research expenditures are based on data assembled by the National Science Foundation (See Table C-I). Research publications refer to scientific papers in the thirteen scientific journals listed below.

Physical Review
Journal of Chemical Physics
Journal of Physical Chemistry
Journal of the American Chemical Society
The Journal of Organic Chemistry
Journal of Applied Physics
Journal of the Acoustical Society of America
Journal of the Electrochemical Society
Transactions of the American Society of Mechanical Engineers
Proceedings of the Institute of Radio Engineers
Review of Scientific Instruments
Annals of Mathematical Statistics
Transactions of the American Mathematical Society

(Biological sciences are not represented in this sample because journals in these fields are very numerous and highly specialized, and the analysis of only a few might lead to misleading results.)

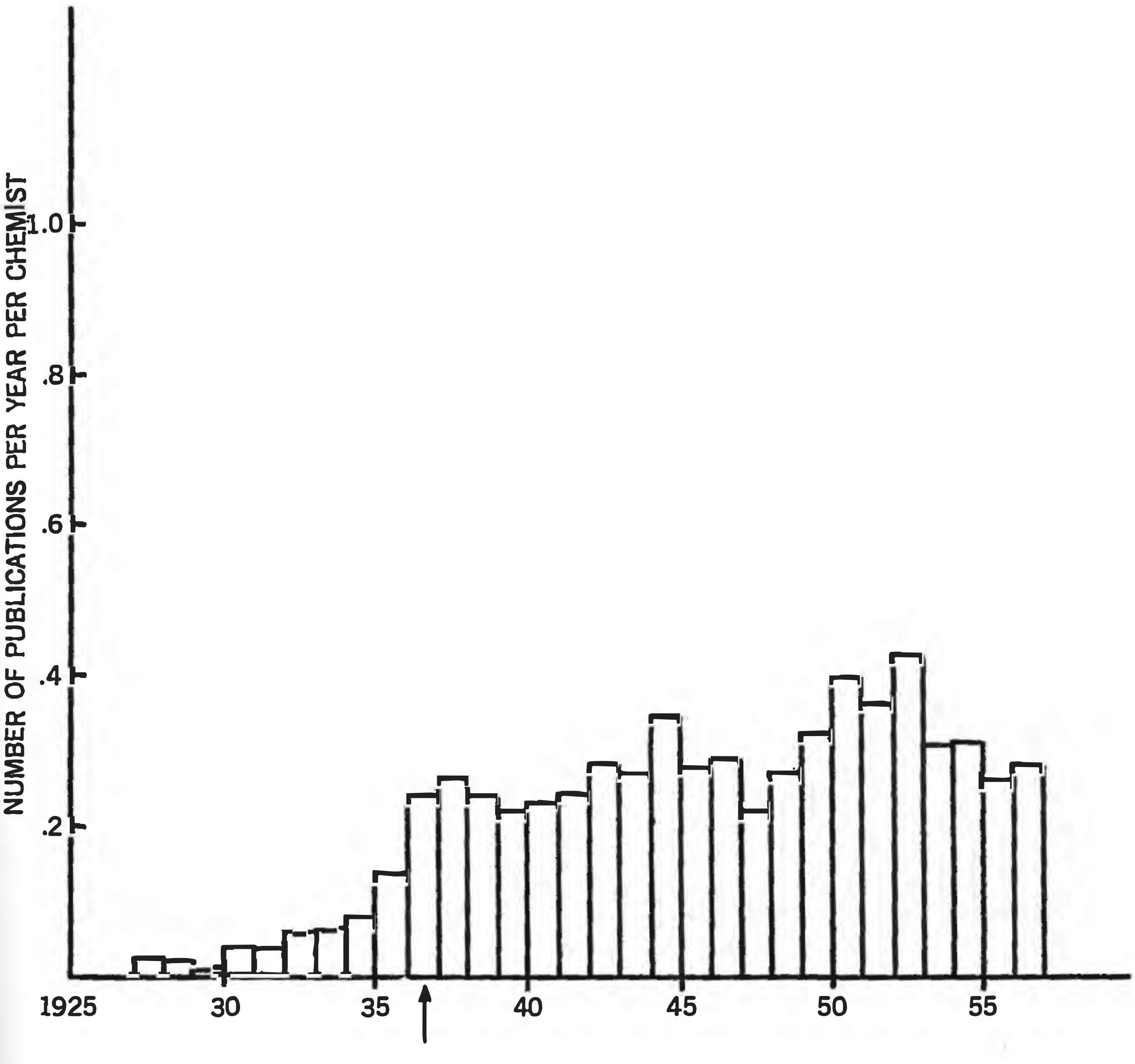

FIGURE C-23
PUBLICATION RATE OF CHEMISTS WHO
OBTAINED Ph.D. IN 1936
(BASED ON ARTICLES SUMMARIZED IN
CHEMICAL ABSTRACTS)

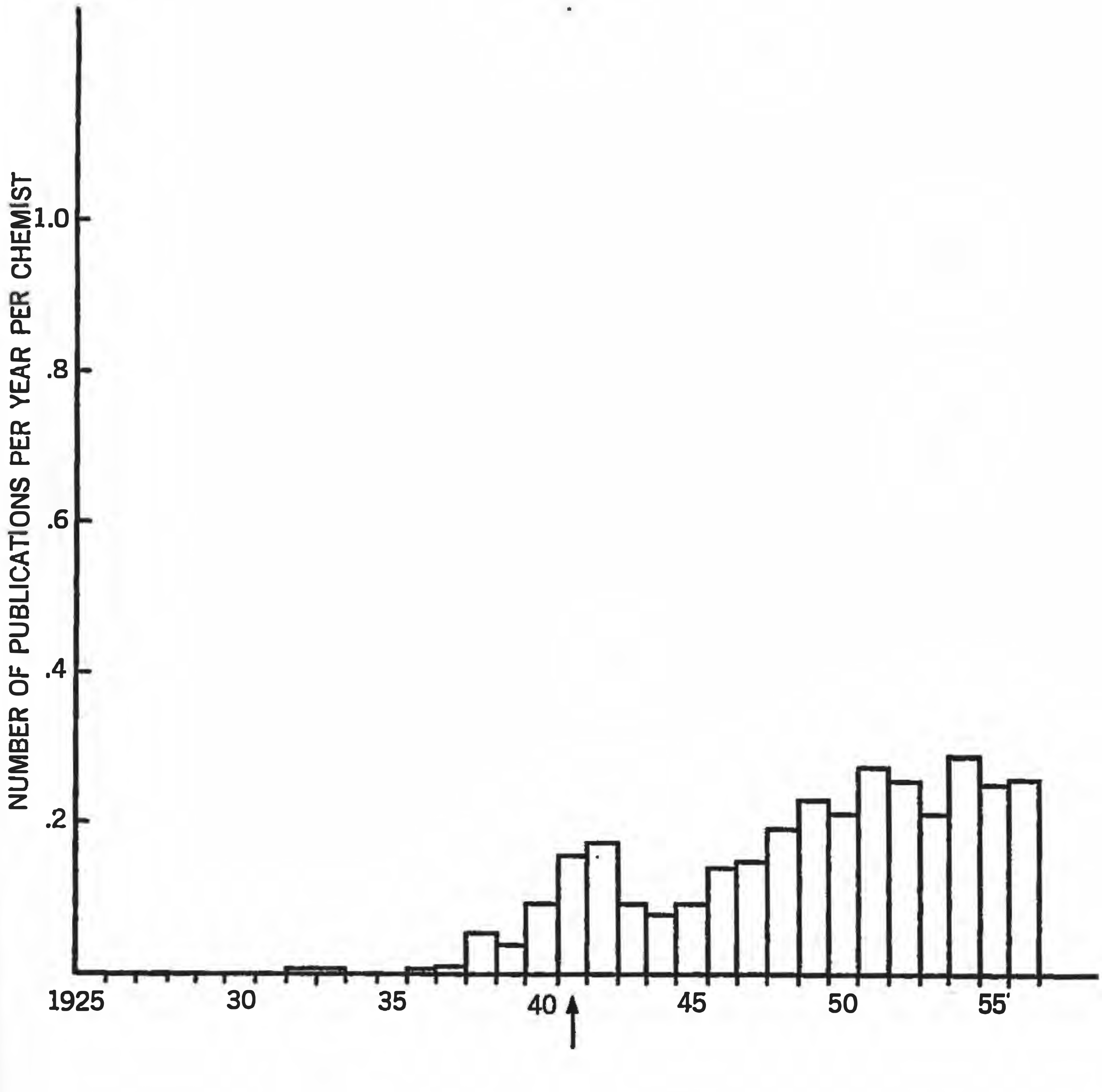

FIGURE C-24
PUBLICATION RATE OF CHEMISTS WHO
OBTAINED Ph.D. IN 1941
(BASED ON ARTICLES SUMMARIZED IN
CHEMICAL ABSTRACTS)

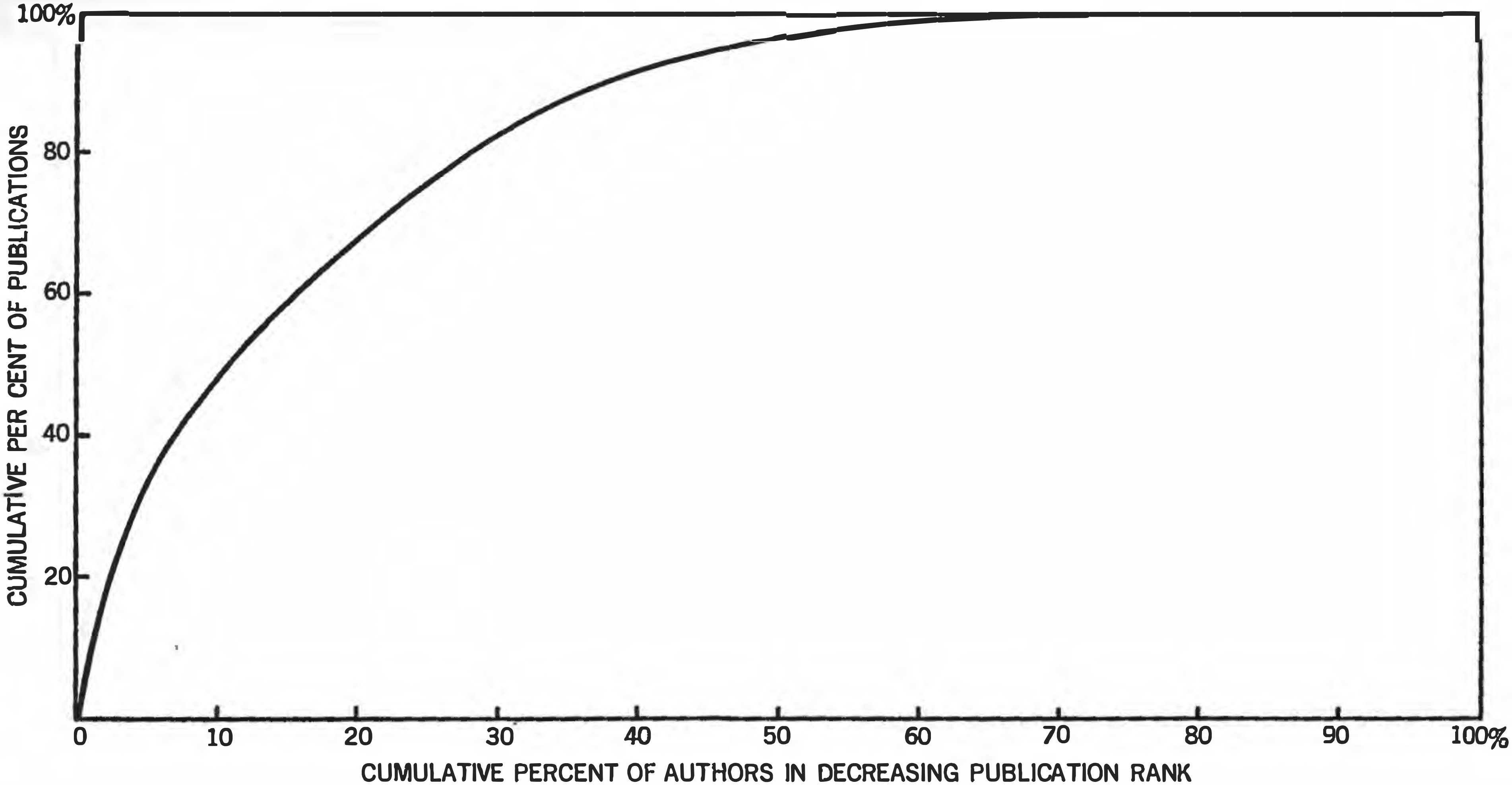

FIGURE C-25
PUBLICATIONS IN *THE JOURNAL OF AMERICAN CHEMICAL SOCIETY* 1927-1956 BY CHEMISTS WHO RECEIVED Ph.D. IN 1936

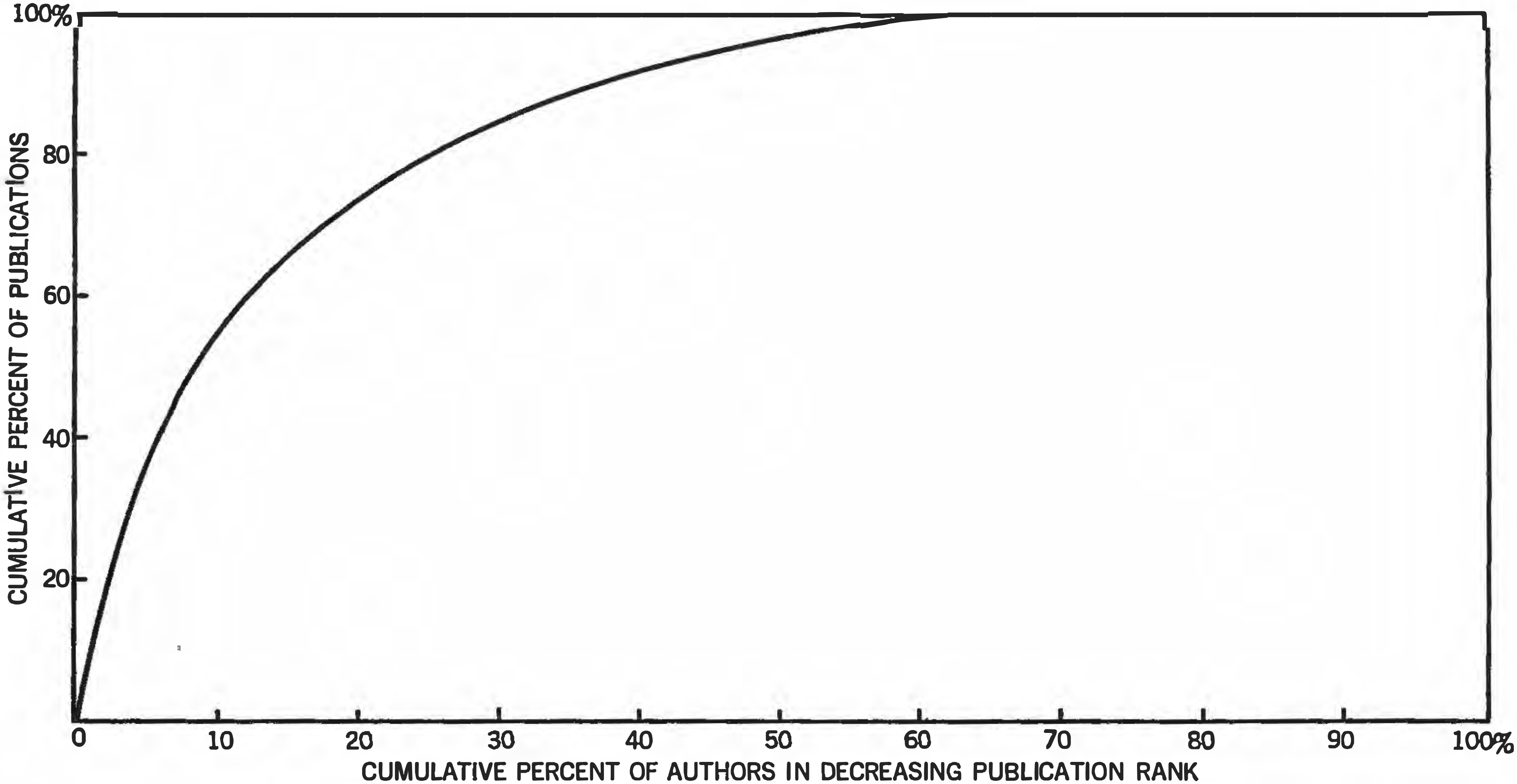

FIGURE C-26
PUBLICATIONS IN *THE JOURNAL OF AMERICAN CHEMICAL SOCIETY* 1939-1956 BY CHEMISTS WHO RECEIVED Ph.D. IN 1936

The number of scientists and engineers engaged in basic research is derived on the assumption that expenditures per man in basic research are comparable with those in research and development activities (See Table C-V).

TABLE C-XII

Basic Research Expenditures, Manpower, and Publications by Type of Research Organization

Type of Organization	Basic Research Expenditure	Publication Rate	Number of Researchers
Government	11%	9%	7%
Industry	39	19	27
Educational and Non-Profit Institutions and Other	50	72	66

Expenditures refer to the fiscal year 1953, whereas publications refer to 1957. This time differential is justified by the following considerations:

1. There is always a considerable delay between the time when research is performed and when results appear in print
2. During the period 1953–1957 no major shifts occurred in research activities or in publication policies.

Government, industry, and educational institutions are all actively engaged in basic research. The three measures of basic research effort employed in the analysis lead to comparable results, with Government laboratories accounting for 10% of the total, industry for 30%, and universities and other non-profit institutions 60%.

Basic Research Requirements and Support

Industry Practice

One approach to the problem of determining the level of basic research effort required by the Department of Defense is to consider industry practices, particularly in fields of rapid technical development and high product obsolescence.

4.5% of industrial R & D expenditures is for basic research

Basic research accounts for approximately 4.5% of all research and development expenditures in industrial laboratories. This figure cannot be directly compared with Government practices because industrial research is centered in relatively few very large companies.

Fourteen chemical, electrical, pharmaceutical, and petroleum companies individually questioned in the course of this study allocate on the average 12.5% of their research and development budget to basic research. Table C-XIII lists the research expenditures of these companies in the years 1947 and 1957. During this period research and development expenditures increased by a factor of 3, and basic research by a factor of 4.5.

In 1957, three companies accounted for 60% of all industry publications in *The Physical Review* (See Table C-XIV).

TABLE C-XIII

Research Expenditures of Sample Companies

Type of Industry	Number of Companies in Sample	1947 Total R & D	1947 Basic Research	1957 Total R & D	1957 Basic Research
Petroleum	4	$ 49 M	$6 M	$180 M	$30 M
Chemical	4	61	7	174	24
Pharmaceutical	3	5	.5	16	2
Electrical	3	148	8	402	44

physics research concentrated in relatively few large industrial laboratories

In 1937 the same three companies accounted for 90%, and in 1949 for 70% of all physics research of a fundamental nature. Thus we see that concentration of physics research in relatively few large laboratories is not a recent development.

A similar picture emerges from a review of thirteen leading scientific and technical journals. Ten companies in the electrical, chemical, and petroleum industry, with 12% of the research and development personnel employed in industry, are responsible for 40% of all industry publications.

In 1957 the combined output of basic research in physics of the three armed services was lower than the output of two industrial corporations: Bell Laboratories and the General Electric Company. The total number of research publications in the physical sciences originating in Government laboratories, both military and non-military, was matched by the output of fifteen leading industrial firms.

TABLE XIV

The Physical Review

Publications Originating in Industrial Laboratories

	1937	1949	1957
Bell Laboratories	3	14	42
General Electric	7	8	27
Westinghouse	2	6	26
RCA	0	3	12
IBM	0	0	5
Other	1	11	42
Industry Total	13	42	154

the Department of Defense, more than any other group, benefits directly from the unpredictable contributions of basic research

On the basis of this evidence, one finds that to achieve the ratio of basic research to research and development expenditures of the larger companies in the electrical, chemical, and pharmaceutical industries, the Department of Defense should increase basic research budgets by approximately 150%. Even greater support of basic research can be justified in view of the magnitude of defense needs and the size of military establishments compared with the size of private corporations. Only organizations with great financial resources, long-range objectives, and very diversified activities can profitably invest in basic research. The Department of Defense, more than any other group, benefits directly from the unpredictable contributions of basic research.

Government-Sponsored Research

In 1956 the research and development budget of the Department of Defense was $1925 million. The Navy Department component was $462 million or 24%. A fraction of these expenditures was allocated to Government laboratories operated by the military services.

Table C-XV shows the number of technical papers contributed to sixteen leading scientific journals by these laboratories in 1956 and 1957. Navy laboratories accounted for two-thirds of the total.

TABLE C-XV

Department of Defense Research Publications 1956–1957

Journal	Number of Publications*		
	Navy	Air Force	Army
Proceedings of the Institute of Radio Engineers	16	6	15
Journal of Applied Mechanics	7	2	3
Journal of Applied Physics	32	3	9
Journal of Chemical Physics	29	15	14
The Physical Review	79	4	7
Journal of American Chemical Society	47	3	26
American Institute of Electrical Engineers	18	2	1
Journal of Optical Society of America	28	10	17
Journal of Physical Chemistry	33	0	5
Journal of the Electrochemical Society	17	1	0
Astrophysics	5	2	0
American Society of Mechanical Engineers	7	2	2
Journal of the Acoustical Society of America	39	18	1
American Society for Testing Materials	2	0	2
Journal of Metals	5	2	5
Industrial and Engineering Chemistry	16	2	10
Total	380	72	117

* Data prepared by Dr. Peter King of the Naval Research Laboratories.

In addition to research performed in Government laboratories, the military services and other Government agencies sponsor research in industry and educational institutions. It is accepted practice for the authors of scientific papers reporting on work supported by Government agencies or private institutions to acknowledge receipt of this support.

We have reviewed the 1957 volumes of *The Physical Review* and of the *Journal of The American Chemical Society* to identify the contribution of the Department of Defense and of the Atomic Energy Commission to research publications in these two journals. Results are summarized in Table C-XVI.

TABLE C-XVI

Research Sponsored by the Department of Defense and the Atomic Energy Commission

Sponsoring Agency	Number of Articles
The Physical Review	
Army	84
Navy	295
Air Force	145
AEC	521
Journal of the American Chemical Society	
Army	76
Navy	79
Air Force	47
AEC	108

Fifty-four percent of the articles published in *The Physical Review* in 1957 reporting on research performed in the United States in non-Government laboratories acknowledge financial assistance from the Department of Defense or the Atomic Energy Commission. Over 90% of this work was performed in educational and other non-profit institutions.

Twelve percent of the articles published in the *Journal of the American Chemical Society* in 1957 reporting on research performed in the United States in non-Government laboratories acknowledge financial assistance from the Department of Defense or the Atomic Energy Commission. Over 95% of this work was performed in educational and other non-profit institutions.

a large potential for research growth exists in academic and industrial laboratories

One way of increasing the national basic research effort is for the Government to expand its role of financial sponsor of meritorious projects. Several studies have indicated that a large potential for research growth exists in academic and industrial laboratories.

Table C-XVII was prepared by the Coordinating Committee on Science of the Department of Defense. It shows the total number and dollar value of meritorious proposals rejected by the Department of Defense in the fiscal year 1957, and the budget for the fiscal year 1958 in each field. Only a small fraction (about 6%) are duplicates. If every proposal classified as meritorious by the Department of Defense were accepted, the contract research program of the Department of Defense would be increased 70%.

The National Science Foundation has reported the data in Table C-XVIII about proposals rejected due to lack of funds. The NSF was able to grant only 28% of the funds requested for meritorious proposals.

TABLE C-XVII

Meritorious Research Proposals
Rejected in Fiscal 1957

Departments of the Army, Navy, and Air Force

	No. of Proposals	Amount	FY 58 Budget Ests. (Basic Research)
Astronomy and Astrophysics	1	$ 9,200	$ 774,000
Biology	16	153,490	3,608,000
Cartography and Geodesy	2	7,375	245,000
Chemistry	101	2,613,282	6,348,000
Combustion	29	1,287,935	2,871,000
Earth Physics	9	142,000	306,000
Geography	7	740,369	824,000
Mathematics	73	1,747,891	4,118,000
Mechanics	90	3,434,648	7,872,000
Medical Sciences	95	1,172,196	9,011,000
Meteorology	9	354,000	1,184,000
Oceanography	22	2,003,700	2,000,000
Physics	302	29,654,499 (16,654,499)**	24,398,000
Psychology	48	1,348,441	1,895,000
Sociology	—	—	156,000
Total	804*	$44,669,026* ($31,669,026)**	$65,610,000

*Duplicate Proposals Included, 50, $2,877,199.

**Total if the $13,000,000 item for a 15–45 Bev Linear Electron Accelerator at Stanford University is eliminated.

TABLE C-XVIII

Meritorious Proposals Received and Grants Awarded 1953–1957
National Science Foundation
(Millions of Dollars)

Fiscal Year	Total Funds Requested	Total Funds Awarded	Meritorious Proposals Not Supported
1953	$ 8.0	$ 1.7	$ 6.3
1954	17.9	3.9	14.0
1955	25.8	7.8	18.0
1956	37.5	9.9	27.6
1957	51.0	15.5	35.5
Total	$140.2	$38.8	$101.4

These data would indicate that there is a drastic shortage of funds to support meritorious research proposals. There are some points to be considered in looking at these estimates:

there is a drastic shortage of funds to support meritorious research proposals

> If funds were increased, requests would also increase. This effect can be seen very clearly in the National Science Foundation data.
>
> The proposals classified as meritorious are rated on the basis of the personal judgment of scientific referees.
>
> If all the meritorious proposals which are submitted to Government agencies were supported, a number of research organizations might find themselves seriously understaffed.

Most research projects cannot be viewed in isolation. An effective research team is assembled slowly over a period of years and cannot contract or expand to respond to changes in the availability of financial resources. The average life of all active contracts in the Contract-Research Program of the Office of Naval Research is five years and two months. Out of a total of 871 projects now actively supported, 251 have been continuous since 1950. We note, however, that 92% of the research agreements between the Office of Naval Research and university and industrial laboratories are due to expire by 1960. Contracts of longer duration would probably prove beneficial both to the Navy and to scientific progress.

Appendix D

Chronology of Naval Technical Developments

This list of events has been prepared to illustrate the impact of science and technology in the evolution of the U. S. Navy. A great many suggestions of items to be included have been received from the various technical agencies within the Navy, and their interest and help are gratefully acknowledged. The authors, however, take full responsibility for the many arbitrary decisions that have necessarily been made regarding those to be listed.

this list of events has been prepared to illustrate the impact of science and technology in the evolution of the U. S. Navy

The objective has been to develop a chronology of reasonable length confined to advances in science and technology originating within or first adopted practically by the Navy. It begins with the foundation of our Republic. It does not include items relating to the navies of other countries, and in general the dates of adoption of such foreign innovations by the U. S. Navy are not included unless there is some unusual reason for so doing, such as situations that reflect conditions peculiar to the United States. Similarly, developments made by other branches of the U. S. Armed Forces have been omitted unless their integration into Navy materiel or operations presented special problems.

Serious effort was made to maintain a suitable balance of emphasis among the various disciplines and technologies. Where U. S. Naval officers are mentioned, their rank at the date of the item has been used.

Time did not permit an exhaustive confirmation of the items, and obviously it was necessary to rely on information received from Navy technical specialists regarding the importance and details of many of those listed. There are naturally opportunities for disagreement with our judgment about the importance or background of the individual developments, but we hope that the chronology will be looked at as a whole, rather than in detail, from the point of view of the increasingly rapid pace at which new scientific discoveries and technological developments are being incorporated into equipment and operations by the Navy.

1777	**Mine** invented by David Bushnell killed three of the crew of the British frigate "Cerberus" at New London when hauled aboard.
	Submarine for military purposes built by David Bushnell, Saybrook, Conn., could support one operator for 30 minutes without a new supply of air.
1787	**First Marine Hospital** founded by the Commonwealth of Virginia at Norfolk to serve the Navy and Merchant Marine.
1789	**Experiments on ships and guns** by Navy authorized by First Congress.
1797	**Frigates** (United States, Constellation, Constitution) launched, more heavily gunned and faster than frigates in any other Navy.
1800	**Submarine** Nautilus built by Robert Fulton while living in Paris.
1801	**Marine Hospital** purchased by the Federal Government as the first U. S. Marine Hospital. It was formerly the Marine Hospital of the Commonwealth of Virginia.
1802	**The New American Practical Navigator** published by Nathaniel Bowditch, adopted by U. S. Navy as standard authority on navigation.
1804	**Catamaran** torpedo invented by Robert Fulton used by British fleet.
1807	Steamboat "Clermont" put in operation by Robert Fulton and R. R. Livingston.
1808	**"Observations on the Means of Preserving the Health of Soldiers and Sailors** and on the Duties of the Medical Department of the Army and Navy, with Remarks on Hospitals and Their Internal Arrangement," believed to be the earliest scientific book by a naval officer, published by Naval Surgeon Edward Cutbush.
1810	**Marine specimens** (shell-fish, etc.) brought from ocean bottom for examination by device invented by Cdr. Stephen Decatur.
1811	Naval **hospital** established by act of Congress.
1814	**Steam-propelled warship**, built by Robert Fulton at a cost of $320,000, launched at Brown's Shipyard, New York, as the "Demologos" or "Fulton the First."
1821	**School for midshipmen** established on board the "Guerierre" in New York City.
1830	**Naval Depot of Charts and Instruments** founded; progenitor of Naval Observatory and Hydrographic Office; observation work in astronomy, magnetism, and meteorology started; 30-inch transit was first astronomical instrument for the Navy.
	U. S. Naval Time Service established.

United States Naval Lyceum formed at the New York Navy Yard under leadership of Capt. M. C. Perry, "to promote the diffusion of useful knowledge." 1833

Mathematical measurement of the base line on Long Island, New York, the first in the United States ever measured scientifically, with participation of Passed Midshipman John A. Dahlgren. 1834

Screw propeller invented by John Ericsson.

New Theoretical and Practical Treatise on Navigation published by Lt. Matthew Fontaine Maury. 1836

Antarctic continent charted on four-year exploration by Lt. Charles Wilkes. 1838

Warship with below-waterline propelling machinery, "Princeton," first screw warship ever built. "Mississippi" commissioned, the U. S. Navy's first ocean-going steam warship. 1841

Naval Observatory began operation. 1844

Naval Academy established at Annapolis (transferred to Newport 1861, returned to Annapolis 1865). 1845

"Wind and Current Charts of the North Atlantic" compiled and published by Lt. Matthew Fontaine Maury. 1847

Experimental naval ordnance firing range established on the Anacostia River by Lt. John A. Dahlgren. 1848

Nautical Almanac Office founded at Cambridge, Mass.; compilation of America's ephemeris begun with Lt. Charles H. Davis as first superintendent of the Office. 1849

"Bottle-shaped" Dahlgren gun, America's first scientifically designed gun. 1850

Measurement of ocean depth by explosive sound attempted by Lt. Matthew Fontaine Maury.

Naval Medical Laboratory founded at Brooklyn, N. Y. 1853

Mines used by the Confederate Navy. 1861

Rifled cannon first tried on a mass basis in the Civil War, and to a limited degree breechloaders also.

Water distilling apparatus improvised on board "Mississippi" to obviate leaving blockade station in order to take on fresh water.

Hospital ship, "Red Rover," used by the Navy. 1862

Iron vessel with turrets, "Monitor," launched at Greenpoint, N. Y.; designed and built by John Ericsson; the revolving turret with which it was equipped was invented by T. R. Timby.

Liquid compasses improved by E. S. Ritchie and (1866) W. R. Hammerslag

1862	**Monitor-Merrimack (CSS Virginia)** clash in Hampton Roads, Va.; first battle between ironclads foreshadows the end of wooden warships.
1863	**National Academy of Science** formed on the initiation of the Navy's Permanent Commission.
1864	**Submarine sinking of enemy ship;** Confederate "David" built by H. L. Hunley sank Federal "Housatonic."
	Transmission of standard time via telegraph, Navy and Western Union.
1866	**Hydrographic Office** established by Congress.
	Steam-driven steering gear introduced; first use of steam to power auxiliary shipboard equipment.
1869	**Torpedo station** established in Newport Harbor.
1873	**U. S. Naval Institute** founded to advance professional, literary, and scientific knowledge in the Navy; Adm. D. D. Porter was first president.
1875	**Steam power** to generate electric power first used aboard ship.
1876	**Torpedo boat,** "Lightning," 58 feet long with a speed of 20 mph, built at Bristol, R. I., by J. B. and N. G. Herreshoff.
1878	**Measurement of velocity of light** by Albert A. Michelson, on equipment constructed himself, while an instructor at the Naval Academy.
1881	**High-powered rifled guns** of "hooped" or "built-up" steel introduced.
1882	**Steel of domestic manufacture** stipulated by legislation for the first ships of the new Navy; this provision gave impetus to American steel industry.
1883	**Ship completely equipped for electric lighting:** "Trenton."
1884	**Naval War College** established.
1886	**Smokeless powder investigations** began at Naval Torpedo Station, Newport, by Charles E. Munroe; reached successful development by 1891.
1887	**Armor-Plate** contract awarded to Bethlehem Iron Company for 6000 tons for the battleships "Maine" and "Texas" and four monitors.
1888	**Effect of hollowed charges** demonstrated by C. E. Munroe at Naval Torpedo Station; applied to bazooka in World War II.
	Experiments with wireless telegraphy on board ship (some years before Marconi's success), by Lt. Bradley Fiske.
1890	**Armored battleship,** "Maine," carrying side armor 12 inches thick, launched.

Smokeless powder grain perforation developed; it is in general use throughout the world today.

Hospital ship, "Solace," fitted out in 1898 and used in the war with Spain. 1898

Naval Model Basin opened at the Navy Yard, Washington, D. C. 1899

Astronomical time reference originated by S. Newcomb. 1900

First submarine in U. S. Navy, "Holland," is commissioned.

Marconi wireless devices installed in three U. S. Naval ships; radio stations erected at Washington, D. C., and the Naval Academy at Annapolis, Md., to test various methods and types of radio equipment.

Smokeless powder plant built at Indian Head to manufacture powders developed at Newport.

Torpedo-Boat Destroyer, "Bainbridge," displacing 420 tons, launched; progenitor of the modern destroyer. 1901

Continuous-aim tracking for guns introduced by Adm. Sims. 1902

Flight of an airplane with three-dimensional controls by Wright Brothers. 1903

Naval Experiment Station and Testing Laboratory authorized by Congress as a result of efforts of RAdm. George W. Melville.

Naval Radio Station established at the Highlands of Navesink, N. J.

Broadcasting of time by radio originated at the U. S. Naval Radio Station, Navesink, N. J. 1904

"Hot running" torpedo, using burning alcohol to increase air pressure, invented by F. M. Leavitt; the "cold running" torpedo powered by compressed air was perfected about 1868 by British engineer Robert Whitehead.

Responsibility for a major portion of Government's use of radio assigned to Navy by President Theodore Roosevelt; at year's end, Navy had 33 ships and 18 shore stations equipped with radio.

Bulbous bow warship, "Delaware," built on design of D. W. Taylor, Naval Model Basin, to reduce ship resistance. 1907

U. S. Navy established as world power as a result of its "Around-The-World-Cruise."

Radiotelephone use on board naval ship achieved. 1908

Surveillance test for smokeless powder stored on ships introduced by G. W. Patterson of the Naval Powder Factory.

U. S. Navy Radio Laboratory, predecessor of the Naval Research Laboratory, is established.

1909 **Annual physical examination** of all officers instituted to determine fitness for duty.

Gyro-compass invented by Elmer Sperry tested on board "Birmingham."

High-power transmitter, a Fessenden 100-KW synchronous rotary spark apparatus contracted for installation at Arlington, Va. This radio station was commissioned in 1913.

1910 **Airplane flight from a ship** made by Eugene Ely, a civilian pilot of the Curtiss Co., from deck of cruiser "Birmingham"; it flew two miles to Willoughby Spit, Va.

"Speed and Power of Ships" published by RAdm. D. W. Taylor, presenting the standard series method of estimating ship resistance.

1911 **Airplane flying school** opened by the Curtiss Exhibition Co.; gave military officers free instruction in flying at the flying field at North Island, San Diego, Calif.

Diesel-powered submarines "Skipjack" and "Sturgeon" launched.

First airplane landing in the world on ship, "Pennsylvania," in San Francisco Bay.

First Navy airplane ordered, Curtiss Triad Amphibian.

Radio installed in naval aircraft for the first time.

1912 **Airplane catapulted** at the Washington Navy Yard, Washington, D. C., from catapult built under the direction of Capt. W. I. Chambers assisted by Naval Constructor H. C. Richardson, launched by Lt. T. G. Ellyson.

Large ship with electrical transmission of power, "Jupiter," built at Navy Yard, Mare Island, Calif., as a collier; it was converted to a carrier in 1922, named "Langley."

Submarine with radio signaling equipment received and transmitted signals off Newport, R. I., at a range of four miles.

Worldwide radio broadcasting of time originated at Naval Radio Station, Arlington, Va.

1913 **Aeronautical Engineering Course** established at Massachusetts Institute of Technology by Lt. Jerome C. Hunsaker.

Continuous radio contact with U. S. mainland maintained during transatlantic voyage, cruiser "Salem."

Photographs taken under sea by J. E. Williamson at Chesapeake Bay by use of Williamson submarine Tube and Photosphere.

1914 **Armor-piercing shell** introduced on wholesale basis.

Iceberg detected by underwater echo ranging, using a form of moving-coil transducer designed by R. A. Fessenden.

World's largest wind tunnel added to facilities of the Naval Model Basin to carry out experimental work in connection with the air resistance of naval vessels and the design of aircraft.

Radio-telephone message transmitted from Naval Wireless Station at Arlington, Va., to Mare Island, Calif. **1915**

Aviation and submarine medicine began to be studied. **1917**

Radio-controlled aircraft experiments begun.

Radiophone fog-warning device, the forerunner of the radio beacon, installed at Point Judith, R. I.

Air control radio system established (4-course radio ranges) to furnish guidance to aircraft. **1918**

Anti-submarine mine barrage laid in the North Sea.

Flight refueling demonstrated by Lt. G. L. Cabot.

High-power, long-wave radio station NSS commissioned at Annapolis, Md., with 350 KW arc equipment.

Mines of the antenna type, firing electrolytically, mass produced.

Most powerful radio transmitting station in the world, 200 KW alternator, installed, New Brunswick, N. J. Navy ships in all parts of the world hear NFF as did field receivers at the front in France. This station flashed President Woodrow Wilson's "Fourteen Points" to Nauen, Germany.

Railroad mounted guns, 14"/50, operated in France and contributed to German decision to cease shelling Paris.

Submerged submarine received and sent radio signals; reception found possible from overseas stations in submarine whose periscope was 21 feet below the surface.

World's first automatic fire control anti-aircraft director and computer system installed to control 5"/25 gun mounts.

First transatlantic flight made by Navy's NC-4; Lt. Cmdr. A. C. Read was in command. **1919**

Measures for safety of minesweepers employed in the sweeping of antenna mines during the clean-up of the North Sea mine barrage.

Radio voice communications transmitted from air to ground.

Feasibility of radio homing by aircraft on vessels at sea demonstrated by Naval Aircraft Radio Laboratory by homing of an F5L naval seaplane to "Ohio." **1920**

Radio Lafayette, near Bordeaux, France, world's first 1000-KW long-wave radio station, commissioned.

Seaplane obtained accurate bearings by radio compass from a battleship off the Virginia coast.

1921	**Non-rigid U. S. Navy dirigible filled with helium** gas, replacing use of hydrogen, operated at Naval Air Station, Hampton Roads, Va.; first practical use of helium gas.
1922	**First Navy all-welded ship,** a fleet tug, was launched at Norfolk Naval Shipyard. This may have been the world's first all-welded ship.
	First radio broadcast by a President of the United States carried out by the Naval Aircraft Radio Laboratory utilizing naval radio stations NSF and NAA.
	Reflection of radio waves from moving ships discovered by Dr. A. Hoyt Taylor and L. C. Young of the Naval Aircraft Radio Laboratory, one of the forerunners of the Naval Research Laboratory. This was the first detection of moving objects by radio, later known as radar.
1923	**Rigid airship** "Shenandoah" constructed; the Navy's rigid airship program established the manufacture of duralumin in this country of which all current airplanes are constructed.
	Airborne high-frequency transmitter and receiver in rigid airship installed by Naval Research Laboratory in "Shenandoah" for trip across the continent and back.
	Naval Research Laboratory, Washington, D. C., placed in commission; recommendation of establishment previously made by Thomas A. Edison.
	Pictures of President Warren G. Harding were transmitted by radio facsimile from Washington, D. C., to Philadelphia, Pa.
	Remote control by radio of a naval ship at sea, "Boggs," demonstrated by Naval Aircraft Radio Laboratory.
1924	**High-power crystal controlled transmitter** installed by Naval Research Laboratory.
	Potentialities of high frequencies for naval communications demonstrated by Naval Research Laboratory, based on its original ionospheric investigations.
	Regular daylight transcontinental radio communications on high frequencies accomplished.
	Remote control of an aircraft by radio demonstrated by Naval Research Laboratory. These experiments presaged guided missiles.
	Vacuum tube transmitters replaced original arc transmitters at NAA, Arlington, Va.
1925	**Height of ionosphere** measured by Naval Research Laboratory and the Carnegie Institution of Washington, D. C.
	Helium in decompression investigated to reduce the time taken in surfacing.

Mechanical television apparatus, using rotating scanning disc, demonstrated.

Radio transmitting equipment embodying the electronic "pulse" principle, later used in radar, developed by Naval Research Laboratory.

Wireless communications maintained on expedition to the North Pole by Donald B. MacMillan with U. S. Naval communications on high frequencies.

Damaging effect of aqueous corrosion simultaneous with cyclic stress demonstrated by work of D. J. McAdam, Jr., who coined term "corrosion fatigue." **1926**

Navy plan for world-wide frequency allocation adopted by International Radio Convention. **1927**

World's first gyro system installed to correct automatically for ship's roll and pitch for gunnery purposes.

Aerial exploration expedition to the Antarctic, including a flight over the South Pole, by Cdr. Richard E. Byrd. The Naval Communications Service rendered wireless service between the expedition units and between the Antarctic and the United States. **1928**

Magnetostriction devices developed suitable for use in generating and receiving underwater sound. **1929**

Naval Ordnance Laboratory established at Navy Yard, Washington, D. C.

Norden automatic bomb sight developed.

Potentialities of very high frequencies (VHF) for naval communications demonstrated by Naval Research Laboratory.

Reflection of radio waves by aircraft in flight discovered by L. A. Hyland; first detection of aircraft by radio. **1930**

Variable pressure water tunnel installed at the Model Basin for study of propeller cavitation.

High-power vacuum-tube transmitters used, first installation in the Philippines. **1932**

"Momsen Lung" used for escape from sunken submarine "Sailfish."

Automatic train and elevation installed on a 5"/25 gun. This is believed to have been the world's first such installation. **1933**

First U. S. stratospheric sealed-cabin balloon flight establishing new world altitude record made by Lt. Cdr. Settle (USN) and Major Fordney (USMC).

All-welded warships introduced. **1934**

First aircraft carrier, "Ranger," designed for the purpose, placed in commission.

1934	**First pulse radar** in the world built and tested at Naval Research Laboratory by L. C. Young and R. M. Page.
	High-pressure high-superheat steam for marine propulsion introduced.
	High-speed computer introduced into study of the anti-aircraft problem; Navy sponsored the development of large high-speed digital computers at the Harvard Computer Laboratory for use in the solution of scientific and engineering problems.
	World's first radar apparatus developed at the Naval Research Laboratory.
1935	**Sonar** development for underwater detection of submarines.
1936	**Transmission and reception of wave pulses by one radar antenna** accomplished.
1938	**IFF equipment for identifying friendly naval aircraft** devised and demonstrated by Naval Research Laboratory.
	Radio systems for homing aircraft on carriers (models YE and YG) devised and demonstrated by Naval Research Laboratory and used by Navy throughout World War II and to date.
	Shipboard operational radar installed, "New York."
1939	**Landing Vehicle Tracked** (LVT) development begun by Marines, which later made possible the attack of coral-protected islands of the Pacific during World War II; formation of doctrine for amphibious warfare completed in 1940.
	Potentialities of ultra high frequencies (UHF) for naval communications demonstrated by Naval Research Laboratory.
	Research in atomic energy and nuclear physics begun at Naval Research Laboratory; first thermal diffusion plant for separation of uranium isotopes.
1940	**David W. Taylor Model Basin** opened at Carderock, Md.
	Degaussing and demagnetization methods for ships developed by Naval Ordnance Laboratory to protect ships from magnetic mines.
	Mobile base hospitals begun, with portable buildings and motorized hospitals.
1941	**Acoustic ray diagrams and sonar prediction charts** developed.
	Fire control radars installed in naval vessels. This is believed to have been the first naval application of radar for gunnery.
	First escort carrier, "Long Island," placed in commission.
	Higgins' boat with bow ramp introduced.
	Lobe comparison techniques developed for determination of sonar bearing deviation.

Radio-sono buoy devised and demonstrated by Naval Research Laboratory. 1941

Teletypewriter circuit installed linking Washington, Norfolk, Philadelphia, New York, New London, Boston and Portsmouth.

Underwater Sound Laboratory established in New London.

Desalination apparatus developed for use on lifeboats and life rafts. 1942

Gyro lead computing gun-sight installed on 20mm AA guns. This is believed to have been the world's first use of the gyro principle for computing gun-sight lead angles.

Homing weapons developed successfully by Bell Telephone Laboratories and Harvard University; homing torpedo completed trial runs.

Jet-assisted Take-off (JATO) used; this may have been the world's first use of rockets for assisting aircraft in takeoff.

Mechanical time fuses of simple economical construction developed by Naval Ordnance Laboratory for anti-aircraft projectiles.

National Naval Medical Center opened at Bethesda, Md., with Naval Medical School, Naval Hospital, Naval Medical Research Institute, Naval Dental School, Naval School of Hospital Administration.

Operational radar arrived in the fleet in quantity to revolutionize tactics and fire control.

Proximity fuze, "VT," developed by OSRD-Navy, successfully tested; "Helena" was first to use it against the enemy in January 1943.

Radar countermeasures intercept receivers and jammers devised and furnished the fleet by Naval Research Laboratory.

Blood plasma used in field surgery. 1943

First guided missile employed in war against an enemy. It was a small drone carrying a 2000-pound bomb.

Homing torpedo used in combat.

Magnetic airborne detector developed by Naval Ordnance Laboratory

Normal mode analysis of low frequency sound propagation in shallow water.

Orr-Trueta fixation and closed method of treating open wounds and compound fractures applied.

Radio countermeasures for guided missiles devised and installed in naval ships by Naval Research Laboratory.

Sound Fixing and Ranging (SOFAR) developed.

1944 **Acoustic depth charge pistol** developed by Naval Ordnance Laboratory.

Clipper correlator and other types of modern signal processing developed for sonar receivers, active and passive.

Electronic aids for swimmers and amphibious forces developed for communication and navigation using underwater sound.

Facsimile (radiophoto) facilities installed at Naval Communications Stations (Washington, D. C., San Francisco, Pearl Harbor, and Guam).

Forward firing rocket attack from U. S. aircraft made against German U-Boat by carrier-based aircraft from "Block Island."

Frequency modulation sonar applied to mine detection.

New landing ships, "Dock Landing Ship (LSD)," "Medium Landing Ship (LSM)," and "Tank Landing Craft (LCT)" introduced.

Pressure mine developed by Naval Ordnance Laboratory.

Radio circuit using Single Side-Band technique became operational between Pearl Harbor, T. H., and Washington, D. C.

Scanning Sonar developed with omnidirectional outgoing pulse and rotating receiving beam.

Shipboard radioteletypewriter equipment successfully tested.

Underwater telephone developed for voice communication using single side-band suppressed carrier, Underwater Sound Laboratory.

1945 **Automatic tracking blindfiring radar directors** installed for anti-aircraft defense. This is believed to have been the first such installation in the world.

Beach mine locator developed for Underwater Demolition Team by the Naval Ordnance Laboratory.

Color facsimile picture transmitted and received over radio circuit.

Convergence zone phenomena discovered in the deep ocean.

"Dunked" sonar developed for use from helicopters.

Guided missile "Bat," only aerial homing missile to be used in World War II, launched from naval aircraft against enemy shipping in Balikpapen Harbor, Borneo.

Modern rocket ships, probably world's first, used in combat at Okinawa.

Facsimile (radiophoto) **photographs of Japanese surrender** transmitted from "Missouri" to the United States.

Ramjet acceleration in supersonic flight demonstrated experimentally by Bureau of Ordnance "Bumblebee" program.

Ramjet aircraft first in flight.

Jet aircraft made successful landings and take-offs from carrier "Franklin D. Roosevelt." **1946**

Michelson Laboratory opened at Naval Ordnance Test Station, Inyokern.

Naval Ordnance Laboratory Magnetic Materials Facility established which produced "Orthonol" (1948), "Bismanol" (1952), "Alfenol" (1953), and "Thermenol" (1954).

New Naval Ordnance Laboratory cornerstone laid at White Oak, Md.

Office of Naval Research established by Congress.

World's record distance flight of over 11,000 miles nonstop and nonrefueled from Perth, Australia, to Columbus, Ohio, made by a P2V Neptune patrol bomber; this record of the "Truculent Turtle" still stands after 12 years.

Development and first successful flights of new plastic balloons starting much scientific research in the upper atmosphere. The nature of primary cosmic radiation was discovered on these flights. Laboratory study of high energy nuclear particles was spurred. **1947**

Guided missile, "Loon," first launched from a submarine.

Official world airspeed record of 650.796 mph. set by Douglas D558 Skystreak.

Ship-to-shore facsimile communication accomplished between an Ice-Breaker ship in the Antarctic and Washington, D. C., 10,581 miles, world record.

U. S. Naval Radiological Defense Laboratory established as a result of Operation "Crossroads."

Cholera treatment on basis of fluid and electrolyte balance. **1948**

Guided missiles experimental and test ship, "Norton Sound," first operated.

Passive sonars developed for submarines practical for 50 to 100 mile range, Underwater Sound Laboratory.

Telemetering of physiological data, air to ground.

"Terrier" guided missile prototype successfully fired.

Viking rocket successful; first high altitude American rocket.

Antiferromagnetism detection by neutron diffraction at the Naval Ordnance Laboratory in conjunction with the Oak Ridge National Laboratory. **1949**

Bone and Tissue Bank established, National Naval Medical Center.

Gasless delay mixtures for use in ordnance developed by the Naval Ordnance Laboratory.

1949 "Lark" guided missile launched from shipboard, "Norton Sound."

Measurement of earth's magnetic field to altitude of 105 km by Naval Ordnance Laboratory in conjunction with the Applied Physics Laboratory of the Johns Hopkins University.

Naval Ordnance Laboratory Aeroballistics Research Facility established.

Real gas effects on flows around blunt shaped bodies at hypersonic speeds first demonstrated experimentally at the Naval Ordnance Laboratory.

Textbook on atomic medicine written by RAdm. C. F. Behrens.

1950 "Albacore" hull form developed by the Bureau of Ships and the David Taylor Model Basin.

Anti-tank aircraft rockets (ATAR) developed, tested and fired in combat, all in period of less than 90 days.

Lightweight titanium alloy developed for use in jet aircraft engines by Bureau of Aeronautics; as strong as high strength steel and only half as heavy.

Submarine radio rescue buoy devised.

Tissue Bank established at National Naval Medical Center.

Anti-fragmentation garment (armored vest) in successful field trial with Marine Corps in Korea.

1951 Distortion of crystal structure lattice constant at paramagnetic-antiferromagnetic Curie temperature discovered at the Naval Ordnance Laboratory.

First U. S. hypersonic wind tunnel operated at Mach 10 without air liquefaction at the Naval Ordnance Laboratory.

First U. S. pressurized ballistics firing range operated at the Naval Ordnance Laboratory.

Moon reflection capabilities for communications demonstrated by Naval Research Laboratory.

Non-destructive inspection of propellant grains by X-ray fluoroscopy developed by the Naval Ordnance Laboratory.

Smoke trail technique and determination of blast from nuclear bombs developed by the Naval Ordnance Laboratory.

Speed record of 1238 mph. and altitude of 79,494 feet attained by Navy Douglas D558-2 Skyrocket in experimental test flights.

Theoretical calculations of heat transfer to body shapes suitable for ballistic missiles conducted at the Naval Ordnance Laboratory.

1952 Minesweeping by helicopter accomplished at the Navy Mine Defense Laboratory, Panama City, Fla.

Rockets from high altitude balloons first fired; threefold height increases resulted.

Theory of noise in semi-conductors developed by the Naval Ordnance Laboratory.

Two U. S. Navy "Terrier" guided missiles destroyed two drone airplanes. These were the world's first cases of destruction of airplanes by surface-to-air guided missiles.

World's largest human centrifuge commissioned at Naval Air Development Center, Johnsville, Pa.

Angled flight deck operational tests begun on "Antietam." **1953**

Chemical finish for fiber glass developed at Naval Ordnance Laboratory; significantly increased strength and stiffness in both wet and dry applications.

Delta-wing jet seaplane made first flight at San Diego.

Farnsworth Lantern adopted as test for color vision.

First carrier-based airplane to hold the official world air-speed record at 752.9 mph., Navy Douglas XF4D-1 Skyray. It also set the 100-kilometer closed course record at 728.11 mph.

First manned aircraft to attain a speed of twice the speed of sound, 1327 mph., Navy Douglas D558-2 Skyrocket. It flew higher (83,235 ft.) than man had ever flown.

Nuclear propulsion prototype plant at Arco, Idaho, first operated on nuclear power.

Sidewinder, air-to-air missile, utilizing heat-seeking or infrared device, test-fired at the Naval Ordnance Test Station, China Lake, Calif.

World's first VTOL airplane, "Pogo," made successful transition from hover to level flight and return to hover.

High sensitivity antisubmarine aircraft-laid bottom mine developed by the Naval Ordnance Laboratory. **1954**

Manned experimental ships successfully maneuvered in fallout from thermonuclear weapons.

Nuclear depth bomb developed by Naval Ordnance Laboratory.

Nuclear submarine, "Nautilus," world's first atomic-powered vessel commissioned.

Passive method of underwater fire control, PUFFS, developed by the Naval Ordnance Laboratory.

Radio-active fallout effects studied in the Marshall Islands.

Voice communication over moon reflection circuit accomplished by Naval Research Laboratory.

World's most powerful VLF radio transmitter (1.2 Mega-watts), Jim Creek Valley station in state of Washington, commissioned.

Freezing whole blood developed as laboratory process for purpose of preservation for clinical use. **1955**

1955 **Guided missile cruiser**, "Boston," placed in commission.

Miss distance indicator developed by the Naval Ordnance Laboratory for determining accuracy of anti-aircraft projectiles or missiles.

Nuclear depth bomb entered stockpile; developed by the Bureau of Ordnance and the AEC.

Record of 695.163 mph. for 500-kilometer closed course set by Navy Douglas A4D-1 Skyhawk.

Teletype transcontinental circuit using moon as a relay established by Naval Research Laboratory.

U. S. Navy's "Terrier" surface-to-air guided missile, worlds' first guided missile to become operational in a fleet; installed aboard "Boston."

1956 **Air-sea-rescue color scheme** designed.

Drugs for prevention and treatment of motion sickness evaluated in sea trials.

Experimental navigational ship, "Compass Island," commissioned to help in scientific development and evaluation of navigation system independent of shore-based aids.

Heat-stress casualties studied with successful revision of training schedules of Marine Corps recruits.

Human Gradient Calorimeter operated at Naval Medical Research Institute, representing first great advance in this type of instrument for over 50 years.

Operationally equipped jet plane, F8U-1 "Crusader," awarded Thompson Trophy, first military airplane to fly faster than 1000 mph.

Rocket-powered helicopter in first successful flight.

Rocket-propelled nuclear weapon entered stockpile.

Solid propellant grains produced of a size applicable to a ballistic missile (Polaris).

Stratolab balloon rose to 76,000 feet in flight designed to gather scientific data at high altitudes; record altitude for manned balloon.

Transoceanic teletype circuit using moon as reflector established by Naval Research Laboratory between Washington, D. C., and Hawaii.

1957 **Arctic ice pack trip** of 1000 miles completed by "Nautilus."

Automatic carrier landing system given first successful test on "Antietam."

Clinical Investigation Center established at U. S. Naval Hospital, Oakland, Calif.

Development of hydrofoils, major improvement in high speed boats. 1957

"Minitrack" radio tracking system employed to track earth-circling satellites.

Plastic balloons became operational instruments for Naval Weather Service with regular unmanned flights across Pacific from Japan to collect wind information at 30,000 feet.

"Solion," a low frequency amplifier operating upon an electrochemical process developed by the Naval Ordnance Laboratory.

Start of astronomical studies from edge of space; first telescope carried on plastic balloon above 95 percent of earth's atmosphere for study of motions in solar atmosphere. Balloon-borne study of Mars begun.

Supersonic transcontinental nonstop flight by F8U-1 "Crusader," "Operation Bullet."

Text and reference work on underwater sound, "Fundamentals of Sonar" by J. W. Horton, published by U. S. Naval Institute.

Theory of Vibrational-Translational Relaxation in Liquids by the Naval Ordnance Laboratory.

Aircraft-laid moored mine developed by the Naval Ordnance Laboratory. 1958

Continuous submersion for 60 days by "Seawolf" without replenishment of air.

First primate in space; a squirrel monkey was fired 280 miles into space in an Army Jupiter vehicle. Animal prepared at National Medical Research Institute and SAM, Pensacola, and telemetering record of data by Navy.

First undersea voyage across the top of the world from Pacific to Atlantic Ocean, a distance of 1830 miles, made by "Nautilus."

"Full Pressure" suit enabled flight surgeon, Dr. Tabor, to live longer at a higher simulated altitude than any other person in history.

Installation of Nuclear Reactor at National Naval Medical Center for preparation of short life radioisotopes.

Lay down bomb developed by the Naval Ordnance Laboratory.

Radio telescope installed for detection of weak signals from the galaxy (and satellites).

Sea level conditions in sealed cabin at high altitude first employed by stratolab manned balloon; transmitted first television pictures from troposphere.

Ship-to-shore message using meteor burst communication technique received at the Naval Electronics Laboratory, San Diego, Calif., from "Tulare" over a distance of approximately 600 miles.

ix-hundred-knot flight gear for weapons developed by the Naval Ordnance Laboratory.

olid fuel fleet ballistic missile "Polaris" test fired.

tellar scintillation observations from stratolab balloon made by A. H. Mikesell, Naval Observatory astronomer.

Submarine to launch guided missiles, "Grayback," commissioned and conducted first test firing.

Supercavitating propeller developed, allowing efficient propulsion at much higher speeds.

Transfusion of human red blood corpuscles preserved for 18 months, U. S. Naval Hospital, Chelsea, Mass.

Vanguard test satellite placed in orbit.

Vulnerability of magnetic materials to neutron irradiation evaluated by the Naval Ordnance Laboratory.

ɔendix E

'erences and
ırce Material

ɘarch and
ɑinistration

' *Public Policy*, Report of President's Scientific Research Board,
ılumes, 1947.

꞉ *Endless Frontier*, Vannevar Bush, 1945.

· *National Conference on Administration of Research*, Penn. State
'ress, 12 meetings, 1947–1958.

· *of Army-ORO Conference on Basic and Applied Research and Com-*
)evelopment, Vol. XI, July 1958.

cement of Medical Research and Education, Report of the Secretary's
Consultants on Medical Research and Education, June 1958.

ıd Development in Industry, A. B. Kinzel, Industrial College of the
Forces, January 1958, L58–89.

the Ad Hoc Committee on Research and Development, Scientific
y Board USAF, June 1958.

ng American Science, President's Science Advisory Committee,
ɔer 1958.

Research Planning Board, Research — A National Resource II
ial Research, 1940.

t and Education, Lecture by R. E. Gibson, Johns Hopkins Univ.

\. Hunter, *Science in the Federal Government*, Cambridge, Mass.:
› Press of Harvard University, 1957.

n K., *Government and Science*, New York: New York University
954.

rvin, *Organizing Scientific Research for War*, Boston: Little, Brown
1948.

Congressional Hearings

Science and Technology Act of 1958, S.4039, June 25, 26, 1958, 25589.

Science and Technology Act of 1958, S.3126, 22380.

Astronautics and Space Exploration, H.R. 11881, 25973.

Department of Defense Appropriations for 1959, H.R. 12738, 26879.

Physical Research Program (AEC) Feb. 1958, 23103.

Department of Defense Appropriations for 1959, 22217.

Research and Development, July 1958, 30694.

Research and Development, August 1958, 29529.

National Science Foundation Publications

"Research and Development and Its Impact on the Economy" NSF.58–36.

"Science and Engineering in American Industry" NSF.56–16.

"Government-University Relationships" NSF.58–10.

"Basic Research A National Resource" NSF.57–35.

"Federal Funds for Science" NSF.57–24.

"Federal Funds for Science" NSF.58–30.

"Scientific Manpower — 1956" NSF.57–23.

"A Selected Bibliography of Research and Development and Its Impact on the Economy." NSF.58–18.

"Federal Financial Support of Physical Facilities and Major Equipment for the Conduct of Scientific Research," June 1957.

Graphics

It would be impractical to include a complete list of books, journals and reports used as source material for the schematic models. The more important references are listed below; the bibliographies in each of these references gives some indication of the volume of source material.

Shock Wave

R. Courant and K. O. Friedrichs, *Supersonic Flow and Shock Waves*, Interscience, New York: 1948.

W. Emmons, "Shock Waves in Aerodynamics," *Journal of Aeronautical* *Science*, Vol. 12, p. 188–194, 1945.

Goldstein, editor. *Modern Developments in Fluid Dynamics*, Oxford University Press, London: 1938.

lected Works of Theodore von Karman, Academic Press, New York: 1957.

H. Shapiro, *The Dynamics and Thermodynamics of Compressible Fluid Flow*, The Ronald Press Company, New York: 1953.

I. Taylor and J. W. Maccoll, "The Mechanics of Compressible Fluids" n Durand's *Aerodynamic Theory*, Vol. III, Div. H, Springer, Berlin: 1934.

von Mises, *Mathematical Theory of Compressible Fluid Flow*, Academic Press, New York: 1958.

dar

E. Guerlac, *A History of Radar* (M.I.T. Research Laboratory for Electronics, Manuscript).

Robert Watson Watt, *Three Steps to Victory*, Odhams, London: 1957.

ansistor

Bardeen, "Research Leading to the Point-Contact Transistor," *Science*, Vol. 126, No. 3264, pp. 105–112, July 19, 1957.

Bardeen and W. H. Brattain, "Physical Principles Involved in Transistor Action," *The Physical Review*, Vol. 75, pp. 1208–1225, April 15, 1949.

ll Laboratories Record, Vol. 36, No. 6, June 1958.

L. Pearson and W. H. Brattain, "History of Semiconductor Research," *Proceedings of the I.R.E.*, Vol. 43, pp. 1794–1806, December 1955.

ceedings of the I.R.E. (Transistor Issue) Vol. 46, No. 6, pp. 947–1346, June 1958.

Seitz, *The Modern Theory of Solids*, New York: McGraw Hill Book Company, 1940.

. Shockley, *Electronics and Holes in Semiconductors*, New York: Van Nostrand, 1950.

H. Wilson, *Semiconductors and Metals*, London: Cambridge University Press, 1939.

fluence of a Man

. H. Beney and O. C. Simpson, "Recent Work in Molecular Beams," *Chem. Rev.* 30, 239, 1942.

G. King and J. R. Zacharias, "Some New Applications and Techniques of Molecular Beams," *Advances in Electronics and Electron Physics VIII*, p. 1 (1956).

I. Estermann, "Molecular Beam Technique," *Review of Modern Physics*, 18, 323; 1946.

R. G. J. Fraser, *Molecular Rays*, London: Cambridge University Press, 1931.

R. G. J. Fraser, *Molecular Beams*, London: Cambridge University Press, 1937.

D. R. Hamilton, "Molecular Beams and Nuclear Moments," *American Journal of Physics* 9, 319; 1941.

J. M. B. Kellogg and S. Millman, "Molecular Beam Magnetic Resonance Method," *Review of Modern Physics* 18, 323; 1946.

N. F. Ramsey, *Molecular Beams*, London: Oxford University Press, 1956.

N. F. Ramsey, *Nuclear Moments*, New York: John Wiley, 1953.

K. F. Smith, *Molecular Beams*, London: Methuen, 1955.