Mission Oriented R&D and the Advancement of Technology

The Impact of NASA Contributions

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MISSION-ORIENTED R & D AND THE ADVANCEMENT OF TECHNOLOGY: THE IMPACT OF NASA CONTRIBUTIONS

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Volume I

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MAJOR FINDINGS

Primary objective of this study was to identify and characterize the nature of NASA contributions to the advancement of major developments in several selected fields of technology. Major developments were identified through interviews with recognized leaders in each of the selected fields while NASA contributions were identified through interviews with NASA scientists, engineers and administrators and an extensive search of the NASA and non-NASA literature.

The major findings of the study follow:

1. NASA contributions to the advancement of major developments in the selected fields of technology appear to be broader, more complex and more indirect than has been realized to date. The number of NASA contributions that find direct nonaerospace applications represent only a small fraction of the large number of contributions that advance the state of technology in a field.

2. Ten dominant types of NASA contributions to the advancement of major developments were identified. Individual contributions identified in this study embodied from one to all ten types. The types include: developing new knowledge; developing new technology; demonstrating the application of new technology for the first time; augmenting existing technology; applying existing technology in a new context; stimulating industry to acquire or develop new technology; identifying problem areas requiring further research; and creating new markets. Certain types of NASA contributions appeared to be more dominant in some fields of technology than in others.

3. The "significance" of most of the NASA contributions was to have caused the technological advancement to occur at an earlier time than it would have occurred otherwise. Significance of NASA contributions varied between fields of technology, with those fields most closely identified with NASA missions, such as cryogenics and telemetry, having the largest proportion of contributions leading to advancements that probably would not have occurred without the NASA contribution.

4. The NASA contributions represented all levels of technology, including major step-changes in technology, incremental advances in technology, and consolidations of technology. Contributions that represented incremental or systematic advances in technology were the most frequent type of contribution, followed by contributions that represented a consolidation of knowledge. Contributions that represented major step-changes were relatively infrequent. Wide differences in these different classes of contribution to different fields of technology were found, depending upon the existing state of technology in the field and NASA's mission requirements.

5. NASA contributions were found in all stages of developmental activity studied, with more than one-half finding military or aerospace applications and almost one-quarter finding commercial applications.

6. When impact was assessed on a linear scale of high, moderate or low, the technological impact of the NASA contributions was estimated to be moderate-to-high, the economic impact to be moderate, the scientific impact to be moderate-to-low, and the direct social impact to be low, with impact varying widely between different fields.

INTRODUCTION

Technological change is a basic charcteristic of our society. Because of this, many people have struggled to assess the influence such change has upon industrial development, economic growth and social advance. Qualitatively, the dependence of a modern economy on the use of new technology is accepted: technology becomes embodied in more effective production machinery, in more skilled labor, and in the products and services that better serve social needs. Quantitatively, the sources of technological change and the relationship between such change and economic and social development has been a continuing source of great controversy.

Before World War II, there was little need to be concerned with this issue at the national level. Most research was performed in universities, American industry carried out developmental efforts supported by their own funds, and national priorities had little direct influence on the allocation of resources to research and development (R & D). With the rapid growth of federally funded military and space R & D activities, a number of important policy questions have arisen dealing with the relationship between R & D and technological progress.

The debate, both public and private, over the role of research in our society, and, in particular, the role of this nation's technological efforts in space has been accelerating. The concept of technological "spin-off" has led both critics and supporters of the space program to look for immediate payoffs from the space program in terms of external applications of the technology derived in the pursuit of the NASA mission. It has been argued by some that much of the technology developed by the space program is irrelevant to the needs of nonaerospace enterprises. Indeed, the products, equipment and techniques developed for use in the space program are motivated by significantly different requirements. Conversely, there have been persuasive arguments raised that the technology now being generated on behalf of the space program has already proven and will continue to prove highly relevant to the civilian economy in the future.

To help resolve this issue, the University of Denver Research Institute (DRI) began, in the summer of 1970, to study the contributions of various NASA activities to major developments in selected fields of technology. This effort was carried out under a contract from the National Aeronautics and Space Administration (NRS 06-004-063). This report presents the findings of that study and should help provide additional insight into the role NASA has played in furthering technological progress.

Initial stimulation for this research effort came from a prior DRI study designed to identify the commercial applications of NASA-developed technology.[1] This earlier study found that the total contribution of aerospace research and development to the commercial economy was broader, more complex, and more indirect, and more difficult to identify than generally realized. This earlier study concluded that: (1) technology, rather than products, was by far the most important contribution of aerospace programs; (2) a portion of the technology advanced by aerospace programs had already found and was expected to continue to find increasing application in commercial industries; (3) a time lag existed between the development of technology for primary aerospace use and its commercial application; and (4) aerospace programs were but one contributor to the advancement of specific technological developments.

These conclusions, and the results of ongoing DRI research aimed at developing a better understanding of how technology generated for government programs is acquired and applied by nonaerospace users, led to the undertaking of this present effort.[2,3]

While a large number of studies of the secondary impact of NASA activities have been carried out over the past few years, most of them involved a common frame of reference: they usually started by tracing the technological or economic impact outward from its point of origin in NASA, such as determining the commercial applications of a particular NASA-developed technological innovation. This project approached the problem from an opposite direction: drawing a sample of major technological developments introduced in a given time period and tracing their origins backward to determine the in-

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1. Welles, J.G., et al. <u>The Commercial Application of Missile/ Space Technology</u>. Denver, Colorado: Denver Research Institute, University of Denver, 1963.

2. The initial concept and methodology for this project were developed by John S. Gilmore and Terry Heller of the University of Denver Research Institute.

3. Project for the Analysis of Technology Transfer, Industrial Economics Division, University of Denver Research Institute, NASA Contract NSR 06-004-063.

fluence of NASA on the advancement of these developments. Several recent studies have attempted this type of approach with varying degrees of success.[1,2,3]

The study was designed to determine how NASA has contributed to the advancement of major developments in specific fields of technology by identifying specific instances of technological contributions, by characterizing the nature and assessing the impacts of these contributions, and by attempting to provide some understanding of the processes by which these contributions enter into the mainstream of technology. Specifically, the project involved these tasks:

- Selecting fields of technology that were of interest to both NASA and the nonaerospace sectors of the economy.

- Identifying major developments in each of the fields over the past decade (and determining the source of these developments) through interviews with acknowledged technical leaders in the field.

- Identifying NASA contributions to the advancement of these developments through interviews with senior NASA technical personnel and analysis of NASA and non-NASA published technical literature.

- Determining the nature and characteristics of the NASA contributions.

- Assessing the influence and impacts of the NASA contributions on the advancement of the developments.

- Identifying the ways in which the NASA contributions were made known outside of the space agency.

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1. Illinois Institute of Technology Research Institute. Technology in Retrospect and Critical Events in Science, (Traces). Chicago: 1969.

2. Sherwin, C.W. "Project Hindsight; A Defense Department Study of the Utility of Research," Science, 156 (June 23, 1967), pp. 1571-1577.

3. Salkovitz, E.I., R.W. Armstrong and J.P. Howe. Case Studies of ONR-Supported Research. Arlington, VA.: Institute for Defense Analysis, October 1970 (Paper P-645).

Attention was concentrated on a limited number of fields of technology in the belief that an in-depth study of a few fields can yield more insights than a less detailed investigation embracing all of NASA's technological efforts. The fields selected included: (1) cryogenics; (2) electrochemical energy conversion and storage; (3) high-temperature ceramics; (4) high-temperature metals; (5) integrated circuits; (6) internal gas dynamics; (7) materials joining processes; (8) materials machining and forming; (9) microwave systems; (10) nondestructive testing; (11) simulation; and (12) telemetry. These fields were selected on the basis of both NASA and nonaerospace activity in the technology, and do not represent a random or representative sample of all of NASA's technological effort or of nonaerospace technological activities. Rather, they represent twelve fields in which NASA has been active and which are economically and technologically important in the nonaerospace sectors of the economy.

While the results of this study do not describe the nature of all of NASA's contributions to all technological advancement and change, they do allow qualitative inferences and assessments to be drawn as to the characteristics, nature, extent and impact of NASA contributions on each of the individual fields, on differences between the fields, and on the group of twelve fields together. **Results developed on the flow of information about NASA contributions are attached in Appendix A.**

I. BACKGROUND

Most people think of a "technology" as a quite specific, physical entity. They do not conceive of this entity as having variable characteristics, changing over time, and made up of many embodied technologies. To most minds, a precisely defined technology will exist in a given situation, or it will not. This misconception causes much of the confusion in discussion about NASA's role in advancing technology.

A "technology" is not a single immutable piece of hardware or a bit of chemistry. While technology may take the form of products, materials, or techniques, it can range from the initial concept of how a basic phenomenon can be applied to the solution of a practical problem, to an end product, device or production machine in a mature operating system. In general, technological developments move through several stages of developmental activity, from concept, through exploratory research, advanced development, and then application. Even when a major development is finding widespread application, it is often undergoing change, adaptation and improvement, and often exists in more than one stage of developmental activity at the same time.

Technology is created for a purpose. While much of it is used only for the purpose for which it was intended, other technology transcends its development and finds use outside of its initial application. A specific process or product may fulfill quite divergent needs and perform very dissimilar functions for its various users. The space program has clearly produced both types of technologies. Within the program, restricted applications of technology are apparent, ranging from control moment gyroscopes to rocket engines. Technology that transcends its initial development also has appeared, such as new high-temperature nickel-base superalloys, new multilayer cryogenic insulation systems and a new solid state x-ray imaging system.

Not only does technology often transcend initial application, much of it is highly pervasive, with the initial application permeating and diffusing through numerous industries and across many fields of technology. This pervasiveness occurs because the technology is often embodied in some device or piece of equipment which is sold or used in different industries for different technological application. Most technology derives immediately from technology that preceded it and, in the main, old technology breeds new technology. For example, the production of stable metal oxide semiconductors (MOS) was made possible, in part, by NASA sponsored development of processes for depositing clean oxide coatings (05-08-02, 05-08-06 and 05-08-07).[1] These devices are now used by an increasingly large and diverse cross-section of American industry and society. Stable MOS devices have found widespread use in products such as computers, portable calculators, and process control instruments. These products are used, in turn, to carry out a variety of technological functions, as for example, temperature regulation in a chemical plant making a synthetic fiber, or computer control of a machining operation in a metal-working plant. The concept of pervasiveness is best explained by understanding that the original NASA contribution to the technology of depositing clean oxide coating is embodied, to some degree, in every product whose manufacture or operation is facilitated by MOS devices.[2]

Almost every field of technology has a wide and relatively continuous range of progress over time. As suggested earlier, most changes or developments in a technological field derive immediately from those that precede them. Progress in a field normally comes in small, continuous increments over time. What may appear to be a "major" change in a field of technology is often an accumulation of small developments which additively made a significant change in the total technology and comprise a major development. An example of this type of incremental advancement is the increase in pressure ratios in gas turbine engines. The increase in pressure ratios over the past decade has been large enough to have affected the efficiency of turbine engines significantly so that it was cited as a major development in the field of internal gas dynamics by experts in that field. However, no single technological event brought about this increase. Rather it was due to a large number of small, incremental events.

However, from time to time, certain discrete changes occur that truly have a significant impact on a field of technology. An example of this is the carbon dioxide laser which was cited as a major development in the field of microwave systems. For the purposes of this study, we have included both types of change (cumulative incremental change and individual change) as major developments in a field of technology.

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1. Complete descriptions of all NASA contributions mentioned in this report are contained in Volume II. Code numbers refer to specific contributions.

2. For a complete case study of NASA's role in advancing the technology of stable MOS devices and their economic impact, see Section IV C of this report.

Advancement in a technological development is usually due to multiple contributions, from many contributors, over time. For example, multilayer metallization is a technique used to make the necessary interconnections on an integrated circuit chip without increasing chip size. Multilayer metallization did not become a practical process until manufacturers of integrated circuits were able to deposit imperfection-free insulating layers of dielectric materials. Contributions to the development of techniques for depositing these layers came from a number of sources, including NASA (05-14-01), and no single source can take complete credit for the development. These techniques represent one step in the development of multilayer metallization fabrication techniques which are now used by almost all semiconductor manufacturing companies for the production of large-scale integrated circuits.

In such a situation, with multiple contributions and multiple contributors, it is difficult, if not impossible, to quantify and assign the exact proportion of benefits attributable to any one contribution. However, a good perspective on the relative numbers and importance of the contributions from any one source, such as NASA, can be obtained by starting with the development at a given time and tabulating and evaluating all of the significant NASA events that contributed towards achieving the advanced state of that development. This does not mean to imply that sole credit for the advancement is due to NASA's contributions (although at times it is) or that the improvements would not have occurred without the NASA efforts (although at times this is also true). Rather, it does indicate that NASA contributed to the advancement, and the benefits attributable to the advancement can be credited, at least in part, to the NASA efforts.

II. NASA CONTRIBUTIONS TO THE ADVANCEMENT OF SELECTED FIELDS OF TECHNOLOGY

NASA contributions to the advancement of major developments in the selected fields of technology appears to be broader, more complex and more indirect than has been realized to date. The number of NASA contributions that find direct nonaerospace applications are but a small fraction of the large number that serve to advance the technology of a field, with consequent technological, scientific, economic and social effects. While precise quantitative measurement is difficult due to the breadth and complexity of the total NASA contribution, examples of certain fields of technology validate this conclusion.

A. Fields of Technology.

Twelve fields of technology were examined for NASA contributions to major developments in each of the fields. The twelve fields studied were the following:[1]

- <u>Cryogenics</u> (01) -- This field of technology encompasses the production, maintenance and application of very low temperatures. The major part of the field is concerned with the liquefaction of gases, and the storage, transport and use of these liquified gases.

- <u>Electrochemical energy conversion and storage</u> (02) -- This field encompasses the storage and direct conversion from chemical to electrical energy through electrochemical processes, including devices such as fuel cells, primary batteries and secondary (rechargeable) batteries.

- <u>High-Temperature Ceramics</u> (03) -- This field includes ceramic materials able to resist the hostile environment of high temperature, and the corrosive effects of highly reactive systems. In the context of this study, we have included those materials capable of withstanding temperatures greater than 2,750 F. and the processes used to form these materials.

- <u>High-Temperature Metals</u> (04) -- This field includes metals designed for use above 1,200 F. broadly

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1. Complete descriptions of these fields are contained in Volume II of this report. Each field is identified by a code number which follows the description of the field. For example, cryogenics (01), electrochemical energy conversion and storage (02), etc.

classified as superalloys (cobalt or nickel-base, depending upon the predominating alloying element) and refractory metal alloys (chromium, columbium, molybdenum, tantalum and tungsten), as well as the technology of forming and fabricating these materials (casting, forging, sintering, etc.).

- Integrated Circuits (05) -- The field of monolithic integrated circuits is based upon fabrication techniques where the silicon semiconductor material itself is the substrate. The active and passive circuit elements are formed by either chemical or physical junction forming processes. The technology of the field includes the design and production of these devices.

- Internal Gas Dynamics (06) -- This field has been limited to the technology of gas turbine engines and the use of such engines in nonaircraft applications. Gas turbines use hot gases directly from a burning fuel to turn the turbine, as opposed to steam turbines which use burning fuel to generate steam which, in turn, drives the turbine.

- Materials Machining and Forming (07) -- This field entails the technology of shaping, forming and finishing materials, and encompasses a broad complex of methods, processes and equipment, including materials cutting and forming machinery, cutting tools, coolants and lubricants.

- Materials Joining Processes (08) -- This field includes such major joining processes as gas, arc and resistance welding; electron beam welding; brazing and soldering; diffusion bonding; and adhesive bonding. Materials, as well as processes, are included.

- Microwave Systems (09) -- Microwaves are very short radiowaves with a frequency range that falls between the UHF (ultrahigh frequency) used for television, and IF (infrared) light bands. Microwaves have characteristics similar to light in that they travel in straight lines, can be reflected, and can be focused in a beam. This field includes the technology of the systems for producing, transmitting and receiving microwaves.

- Nondestructive Testing (10) -- This field covers techniques for the analysis of material properties without impairing the properties (NDT), and the concomitant step of evaluating the material thus analyzed, which is termed nondestructive evaluation (NDE).

- Simulation (11) -- The technology of this field involves the development and use of mathematical and physical models of various complex systems, for purposes of prediction, analysis, decision-making, and training. Many of the models use computers (digital, analog or hybrid) to simulate the interactions of physical, managerial, political and social systems.

- Telemetry (12) -- This field deals with the presentation of measured data at a location remote from the source of the data and involves the generation of a signal which measures the pertinent physical variables, transmission of the information, and conversion of the data into a form appropriate for display, recording or further processing.

B. Characterization of NASA Contributions.

To better understand the nature and extent of NASA contributions to the advancement of technology, this study focused only on major developments occurring in each field during the last decade, and not on all developments in the field. A total of 263 major developments were identified through 161 interviews with recognized technical leaders in the twelve selected fields of technology.

Identification of NASA contributions was limited to a few selected major developments in each field with 109 developments, or 40 percent of the total cited, selected for further study. Selection was on the basis of a general consensus among those interviewed and after discussion with scientists, engineers and specialists in each of the fields. Such lists of major developments are always arbitrary to some extent, with questions as to why some developments were included and others not included. In addition, there is some evidence to suggest that less spectacular, follow-on developments in a field may be more important in the aggregate than more identifiable major developments. Nevertheless, while there may be some questions as to whether the selected developments are the most important in the field, they are certainly considered among the most important.

NASA contributions to the advancement of the selected developments were then identified through interviews with key NASA technical personnel and through search and analysis of both NASA and non-NASA scientific and technical literature. This process resulted in the identification of 366 NASA contributions to the advancement of the selected major developments in the twelve fields of technology. Contributions per field ranged from a low of 14 in telemetry to a high of 61 in high-temperature metals, with an overall average of approximately 30 NASA contributions per field. Each contribution was characterized by type of contribution, degree of technological change the contribution represents, significance, impact and stage of developmental activity.

The identified NASA contributions can be considered neither a complete listing, i.e., a census, nor representative (in the statistical sense) of what may actually exist. It is doubtful that a complete listing can be compiled, regardless of study effort. However, an attempt was made to construct a reasonable sample of contributions to permit generalizations of certain study results. The contributions presented in this study represent only a fraction of the items identified in interviews with NASA personnel or through the literature searches. It was impossible in certain cases to obtain sufficient details to be reasonably certain the items qualified as contributions. In other cases, it was apparent that the items, while representing sound technological efforts designed to help achieve NASA's mission, did not serve to advance the development. In addition, only those contributions that could clearly be identified with NASA were included. Since it is difficult at times to draw clear boundaries between military and civilian space activities, some NASA contributions were undoubtedly missed.

1. Types of NASA Contributions

Ten dominant categories of NASA contributions were identified. These ten categories include:

- Developing new scientific or technological knowledge.
- Developing new technology.
- Demonstrating the application of new technology for the first time.
- Augmenting existing technology.
- Applying existing technology in a new context.
- Stimulating industry to acquire or develop new technology.
- Disseminating scientific or technical information.
- Providing technical assistance.
- Identifying problem areas.
- Creating and supporting new technological markets.

The categories are not mutually exclusive, and it is more the rule than the exception to have one contribution embody several different categories of contribution. A list of the dominant types of NASA contributions to each of the fields of technology is given in Table 1.

- Developing new scientific and technological knowledge. New knowledge is generated by basic and applied research carried out directly by NASA and its contractors, or indirectly through industry funding motivated by potential NASA markets. This type of contribution generates the kind of knowledge that is potentially applicable and useful to many fields of technology. However, since it is several steps removed from ultimate application, it is one of the most difficult to identify and discuss in concrete terms.

  An example of this type of NASA contribution is an advanced understanding of the physical properties of the silicon-silicon dioxide interface which was developed by Philco-Ford under a contract with NASA (05-08-02). This understanding represented a major contribution to determining the failure modes of multilayer large-scale integrated (LSI) circuits and served as the basis for developing techniques to improve the reliability and performance of LSI devices.

  Of the total NASA contributions to the twelve fields of technology, 33 percent were included in this category.[1]

- Developing new technology. A second type of contribution to the advancement of major developments comes in the area of developing new technology. This type of contribution is different from the development of new knowledge in that the ultimate contribution is a distinct and often clearly identifiable product, process, technique, method or material. A good example of this type of contribution is the development of a laser system for the nondestructive testing of solder joints to predict printed circuit board lifetime (10-08-03). This system was developed to meet NASA's high reliability requirements and to reduce the cost of extensive circuit board failures.

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1. Percentages listed for each of these types of contribution will add to more than 100 due to the fact that most contributions are included in two or more different categories.

TABLE 1

DOMINANT TYPES OF NASA CONTRIBUTIONS TO MAJOR DEVELOPMENTS IN SELECTED FIELDS OF TECHNOLOGY

Type of Contribution	Cryogenics	Energy conversion	Ceramics	Metals	Integrated circuits	Gas dynamics	Machining	Materials Joining	Microwave systems	NDT	Simulation	Telemetry	12 Fields Averaged
Developing new scientific and technological knowledge	X	X	X	X	X	X	X	X	X	X		X	X
Developing new technology (products, processes, methods, etc.)	X	X	X	X	X	X	X	X	X	X	X	X	X
Demonstrating the application of new technology					X				X		X	X	
Augmenting existing technology	X	X	X	X	X	X	X						X
Applying existing technology in a new context		X	X		X	X			X		X	X	X
Stimulating industry	X	X			X	X					X	X	
Evaluating and disseminating scientific and technical information	X			X		X	X	X		X	X	X	X
Providing technical assistance	X				X	X	X					X	
Identifying problem areas	X				X	X	X		X			X	
Creating and supporting new markets	X				X	X	X		X			X	

Another example is the development of a technique to locate leak paths in integrated circuit multi-leaded devices (05-08-05). This technique was needed because moisture leaking into the seals used in the multi-leaded package containing the semiconductor chip is one of the major causes of instability affecting the reliability of integrated circuits. Prior to this development by NASA it was impossible to detect all of the leak paths. This technique is now used by almost all of the major semiconductor manufacturing companies.

Approximately 57 percent of the total NASA contributions include the development of new technology. These technological contributions were made up of 30 percent new products, 17 percent new processes, 44 percent new methods or techniques and 9 percent new materials.

- Demonstrating the use of new technology. To gain widespread acceptance, new technology requires visible application so that its potential can be demonstrated. NASA has taken new technology that was developed outside of the space agency for nonspace uses, and tested, evaluated and applied the technology for the first time, thereby demonstrating the feasibility of the technology and often improving it in the process. An example of this type of contribution was the early application of directional solidification techniques by NASA to produce superalloys with improved high-temperature properties (04-06-02). Approximately 8 percent of the total NASA contributions fall into this category.

- Augmenting existing technology. In this category are included products, processes, materials and techniques which were originally developed for non-NASA use and which have been adapted or improved by augmenting the existing technology so as to meet NASA requirements. An example of this type of contribution was the modification of metal oxide semiconductor/field effect transistors (MOS/FET) by implanting boron atoms so that defective devices could be remotely restored after breakdown (05-08-01). Another example is the improvement in intermediate strength and ductility of commercial nickel-base superalloys by thermomechanical processing (04-10-03). Approximately 22 percent of the NASA contributions to the combined twelve fields represented the augmentation of existing technology.

- <u>Applying existing technology in a new context</u>. As with the augmentation of existing technology, NASA and its contractors often apply existing technology in a new context so as to meet NASA needs. Good examples of this type of contribution are the application of ion implantation techniques to produce microwave integrated circuits (09-17-01), and the application of these same types of techniques to control the location of p-type carriers in semiconductor lasers (09-19-02). While ion implantation techniques were already in use for other types of devices, the NASA contributions demonstrated the power and effectiveness of the technique in other areas. This category includes approximately 14 percent of the total NASA contributions.

- <u>Stimulating industry</u>. Industry has often been stimulated to carry out its own research and development, to develop new products or processes, and to acquire technological skills and equipment in order to meet NASA requirements and exploit NASA markets. An example of NASA's role in this type of contribution was in stimulating industrial suppliers of pre-alloyed superalloy powders, such as Federal Mogul and Cabot Industries, to improve their products and processes (04-07-03). While both of these firms were already producing some pre-alloyed powders, they modified their formulations to meet NASA's alloy needs, thereby enlarging their product line. Another example was the entry of RCA into the Gunn effect device market to meet NASA market requirements (09-05-02). The NASA requirement stimulated RCA to enter the market and become a supplier of such devices sooner than they probably would have on their own.

  Approximately 19 percent of the total NASA contributions represent a stimulation of industry to carry out or advance its technological activities. This contribution is almost evenly divided between stimulating industry to carry out its own research and development, to develop new products and processes, and to acquire technological skills and equipment.

- <u>Disseminating scientific and technical information</u>. It is characteristic of a rapidly advancing field of technology to be developed by numerous researchers and organizations. Not only are these scattered information sources difficult for the technologist and scientist to identify and acquire, but there is a continuing problem of duplicating research. NASA has routinely evaluated existing technological information, compiled this information in a usable form, and disseminated it widely throughout industry. Numerous examples of this type of contribution exist, including the preparation of NDT handbooks (10-11-15), the preparation of a cryogenic data handbook (01-11-10), and the development of a comprehensive aluminum alloy welding textbook (08-01-03). Almost 20 percent of the total NASA contributions fall into this category.

- <u>Providing technical assistance</u>. Because NASA is often simultaneously involved in advancing a technology and in assuring proper application of the technology on its contracts, NASA personnel are in almost daily professional contact with corresponding workers in other government agencies and industrial firms. Technical service in overcoming difficult technical problems has been provided to industry in the form of facilities as well as information. Examples include improving commercial NDT capabilities through NASA technical assistance (10-11-01), developing commercial electric discharge machining capabilities (07-05-01), and assisting commercial machine shops in acquiring the necessary tools and skills to perform advanced numerically controlled fabrication (07-12-02). Nine percent of the total contributions take the form of technical assistance, with approximately one-third of the assistance coming as facilities, such as the use of NASA equipment, and two-thirds as information and advice.

- <u>Identifying problem areas requiring further research</u>. Because the existing state of technology of a particular development or field often does not meet space program needs, NASA has periodically undertaken systematic and critical evaluations of existing levels of competency and practice. These evaluations have resulted in the identification of key problem areas and the setting of priorities for research and advanced development. A good example of this is the massive NASA-funded aluminum welding development program, which represented a major contribution to the advancement of aluminum welding technology (08-01-01). The aim of this effort was to solve common welding problems, avoid duplications of effort, and define those areas requiring further research. Another example is the leadership provided by NASA in coordinating aircraft noise reduction research, including the identifications of key research problems and the setting of national research priorities (06-13-07). Thirteen percent of the NASA contributions are in this category.

- Creating and supporting new markets. Due to the large-scale purchase of new technological supplies and equipment, NASA is often involved in the early support of markets, including creating or supporting the market, developing competitive suppliers and creating new firms. Examples include: providing a major market for cryoinsulation materials long before commercial support was feasible resulting in availability of cryoinsulation in a quantity and at a price that would not have been otherwise possible at that early stage of development (01-06-07); development and early support of commercial markets for specialized MOS integrated circuits (05-08-03); and development of a competitive commercial market in the multilayer metallization field (05-14-04). NASA contributions in this category amount to 9 percent of the total, with 70 percent of this contribution in the form of creating new markets, 24 percent in the form of developing competitive suppliers and 6 percent in the form of creating new firms.

2. Level of Technological change of NASA Contributions

NASA contributions were also categorized as to the level of technological change which they represented. A class I technological contribution represents a "step function" change in the technology of the development; a class II technological contribution represents an incremental or systematic advance in the technology of the development; and a class III technological contribution represents a consolidation of knowledge within the development.

A good example is the advancement of powder metallurgy techniques in the field of high-temperature metals. The development of a totally new approach for making high-purity, finely divided metal powders using an electron beam process (04-16-06) was considered a class I contribution since it represented a significant change and an entirely new way of producing powders. The development of an improved, relatively low-cost, powder metallurgical technique to produce porous refractory metals with predetermined pore size and density (04-16-09) was characterized as a class II contribution since it represented a systematic advance in the technology of producing refractory metal powder bodies. Finally, the establishment of industrial health guidelines to reduce health hazards associated with metal powders (04-16-08) was a class III contribution since the advancement in the development was achieved through a consolidation of existing technological knowledge rather than through a change or advance in the technology. Certain types of contributions to the advancement of a development, generally nontechnological in character, cannot be characterized as to class of technology, such as the early support of a market or the providing of technical service.

As would be expected, class I contributions are relatively infrequent events, while class II contributions occur with the greatest regularity. However, the distribution of class of NASA contributions varies greatly from field to field, as shown in Table 2. While class I NASA contributions represented only 6.3 percent of those identified for all twelve fields, this category ranged from a high of 25 percent of the contributions in ceramics to none in fields such as joining and machining. Class II contributions amounted to 64.8 percent of the total NASA contributions, while class III contributions amounted to 23.3 percent. Nontechnological contributions amounted to a little more than 5 percent of the total.

The wide differences in class of technology of NASA contributions to different fields of technology is an indication of the existing state of technology in any given field and NASA's technological requirements. For example, nobody before had ever had to meet the requirements for deep space communications that NASA faced. That NASA had to develop this new and different technology is reflected in the high proportion of class I contributions that NASA made to the field of telemetry. In contrast, the lack of class I NASA contributions in fields such as machining and joining reflect the basic state of technology in those fields and NASA's attempts to use and improve this technology to meet its mission requirement, rather than to develop wholly new technological developments.

3. Significance of NASA Contributions

The concept of class of contribution should not be confused with the significance or impact of the contribution. Class of contribution is a characterization based solely upon the type of technological change, and not the effect the contribution has on the development or the environment in which the development exists.

For the purposes of this study we have defined significance as the effect the contribution had on the occurrence of the advancement of the development. Or, in other words, did the contribution have any effect on whether the advancement occurred or when the advancement occurred? Significance of a contribution was characterized by five different effects: (1) entire development attributed to NASA; (2) advancement would not have occurred without NASA contributions; (3) advancement occurred earlier than would have due to NASA contributions; (4) advancement occurred due to parallel contributions of NASA and others; and (5) NASA contribution had a minor effect on the advancement.

TABLE 2

CLASS OF TECHNOLOGY OF NASA CONTRIBUTIONS TO
MAJOR DEVELOPMENTS IN SELECTED FIELDS OF TECHNOLOGY

	Class of Technology, Percent			
Field of Technology	Technological Change Class I	Technological Change Class II	Technological Change Class III	Nontechnical Contribution
Cryogenics	6.3	56.2	25.0	12.5
Energy conversion	3.8	73.2	19.2	3.8
Ceramics	25.0	54.2	20.8	--
Metals	6.6	68.8	24.6	--
Integrated circuits	6.7	73.3	13.3	6.7
Gas dynamics	4.0	60.0	24.0	12.0
Machining	--	59.1	27.3	13.6
Materials joining	--	76.8	20.9	2.3
Microwaves	--	76.5	17.6	5.9
NDT	9.7	54.8	29.0	6.5
Simulation	--	62.5	37.5	--
Telemetry	21.4	57.2	21.4	--
Twelve fields averaged	6.3	64.8	23.2	5.2

Using these categories, NASA scientists, engineers and administrators were asked to subjectively assess the significance of their own contribution, and the NASA contributions with which they were most familiar. Each NASA assessment was reviewed by two members of the project team. In those cases where a NASA assessment of the significance of a contribution could not be obtained, the assessment was made by the analyst on the project team responsible for that particular field of technology. These judgements were, in turn, reviewed by another member of the team. Significance of NASA contributions is shown in Table 3.

In the first category, the development and the NASA contribution are one and the same. That is, the development was solely attributable to NASA. One such case is the computer enhancement of radiographs, which was cited by experts as a major development in the field of nondestructive testing (10-03-01). NASA was responsible for developing these computer enhancement techniques, rather than just contributing to the advancement of the techniques. Five of the 109 major developments cited by experts and selected for searching for NASA contributions, or almost 5 percent of the total, were attributable solely to NASA efforts. These five developments are: high-frequency power transistors (09-06-01) in the field of microwave systems; computer enhanced radiography (10-03-01), delta scanning (10-04-01), and solid state radiographic image amplifiers (10-04-01) in the field of nondestructive testing; and the simulation of lunar landings (11-10-01) in the field of simulation.

While the five NASA developments in this category represent 5 percent of the total developments selected for searching, they represent only 1 percent of the 366 NASA contributions identified in the study.

Included in the second category are those advancements that probably would not have occurred without the NASA contribution, such as the development of a system to collect data from a remote moving transmitter via satellite (12-15-02). Four fields contain a relatively high percentage of advancements that would not have occurred without the NASA contributions. These are cryogenics (23 percent), integrated circuits (20 percent), simulation (29 percent) and telemetry (36 percent). In light of NASA's unique requirements in each of these fields, this distribution is not surprising. Overall, only 12 percent of the total NASA contributions are in this category.

The most dominant category for NASA contributions is the third: advancements which occurred earlier than they would have without the NASA contribution. Examples include development of a circuit concept design for epitaxial base resistors (05-03-03); demonstration of the use of computers to synthesize circuits from input-output specifications (05-05-01); and the development of manufacturing processes for TD-nichrome sheet (04-04-04). Almost 78 percent of the total NASA contributions are estimated to have brought about the advancement of a development earlier than it would have occurred otherwise.

TABLE 3

SIGNIFICANCE OF NASA CONTRIBUTIONS TO THE ADVANCEMENT OF MAJOR DEVELOPMENTS IN SELECTED FIELDS OF TECHNOLOGY

	Percent Distribution				
	Entire development attributed to NASA	Advancement would not have occurred without NASA contributions	Advancement occurred earlier than would have due to NASA contributions	Advancement occurred due to parallel contributions of NASA and others	NASA contribution had minor effect on advancement
Cryogenics	--	22.9	77.1	--	--
Energy conversion	--	7.4	33.3	37.1	22.2
High-temp. ceramics	--	--	95.8	4.2	--
High-temp. metals	--	8.2	88.5	3.3	--
Integrated circuits	--	20.0	72.5	7.5	--
Gas dynamics	--	--	92.0	8.0	--
Machining and forming	--	9.1	86.4	4.5	--
Materials joining	--	9.3	90.7	--	--
Microwave systems	5.9	5.9	70.5	11.8	5.9
NDT	9.7	--	80.6	3.2	6.5
Simulation	4.2	29.2	54.2	12.5	--
Telemetry	--	35.7	57.1	7.2	--
Twelve fields averaged	1.4	12.0	77.6	7.4	2.5

TABLE 4

STAGE OF DEVELOPMENTAL ACTIVITY OF NASA CONTRIBUTIONS
TO THE ADVANCEMENT OF MAJOR DEVELOPMENTS IN
SELECTED FIELDS OF TECHNOLOGY

	Stage of Developmental Activity, Percent*				
	Concept	Exploratory Research	Advanced Development	Military or aerospace Applications	Commercial Applications
Cryogenics	--	--	12.5	64.6	45.8
Energy conversion	--	44.4	44.4	33.9	14.8
High-temp. ceramics	4.2	16.7	50.0	29.2	12.5
High-temp. metals	--	13.1	44.3	41.0	16.4
Internal gas dynamics	4.0	4.0	40.0	28.0	24.0
Integrated circuits	--	10.0	16.7	60.0	53.3
Machining and forming	--	--	--	72.7	13.6
Materials joining	--	--	--	79.1	16.3
Microwave systems	5.9	35.3	5.9	35.3	17.6
NDT	--	--	22.6	61.3	9.7
Simulation	4.2	37.5	41.7	75.0	16.7
Telemetry	7.1	--	28.6	64.3	21.4
Twelve fields averaged	1.4	11.7	25.7	54.4	23.0

* Percentage distribution can add to more than 100 in any one field of technology due to the fact that a NASA contribution can be in one or more stages of development at the same time.

In the fourth category are those advancements which occurred due to parallel contributions of NASA and others. Examples here include a method for interconnecting cased analog and digital silicon chips (05-14-01) and the development of sensitive subcarrier modulation and synchronization equipment necessary for coded communications (12-11-01). Only 7 percent of the total fell into this grouping.

The final category includes those contributions that had little, if any, effect on the timing of the advancement, such as a NASA-funded development of computer models of TRAPATT diodes (09-21-01). This category amounted to less than 3 percent of the total.

4. Stage of Developmental Activity

As with major technological developments, NASA technological contribtuions can be classified as to the stage of developmental activity they are in. A contribution can be in an early concept stage, it can be in exploratory research or advanced development, it can be finding aerospace or commercial applications, or it can be in some combination of two or more of these stages at the same time. Certain non-technological contributions, such as providing technical service, identifying new problem areas or disseminating scientific or technical information, do not pass through these stages of technological development and therefore cannot be characterized using this parameter.

The stages of developmental activity for each of the fields of technology is given in Table 4. For the twelve fields averaged, more than one-half of the NASA contributions were finding aerospace or military applications at this time, and almost one-quarter were finding commercial applications. Commercial applications by field ranged from a high of 53.3 percent of the contributions in integrated circuits to a low of 9.7 percent of the contributions in NDT.

III. MEASURING THE IMPACT OF NASA CONTRIBUTIONS

Measuring innovative activity is itself a formidable problem which has not been solved to anyone's satisfaction. Moving from a measure of this activity to a measure of economic impact greatly increases the problem. Focusing the task on measurement of the economic impact of NASA's technological efforts reduces few problems and adds many. One recent attempt to measure the overall economic impact of technological progress appears to have met with some success.[1]

A. Quantitative Assessment

The measurement process associated with quantifying the economic benefits of the NASA contributions in this study would require the three following steps: (1) identification of technological advances and NASA contributions; (2) estimation of economic benefits attributable to the advances; and (3) isolation of the links between the NASA contributions and the advances from among diverse other contributions. The first step has already been accomplished for a sizeable sample of technologies. Measuring the benefits of new technological advances -- the second step -- requires benefit/cost analysis. It is on the third step that the most difficult challenges arise. The knowledge and techniques needed to assess the relative economic contribution of one agency in a multi-agency development and diffusion process appears to be beyond the present state of the art.

1. Measuring the Benefits

During the past two decades considerable progress has been made on the theory and practive of benefit/cost analysis.[2] One pioneering example of the research and development area was Griliches' study of the economic benefits from hybrid corn research, in which he found the return on research investment to be approximately 700 percent.[3] Most of the NASA contributions that were identified in this study, however, present more difficult estimation problems. Perhaps most important, corn is a simple, nearly homogeneous product, while many of the NASA contributions have multiple nonaerospace applications.

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1. Economic Impact of Stimulated Technological Activity. Part I: Overall Economic Impact of Technological Progress -- Its Measurement. Kansas City, Missouri: Midwest Research Institute, Final Report 7, April 1970-15 April 1971 (NASA Contract NASW-2030).

2. For a general survey, see Roland N. McKean, Efficiency in Government Through Systems Analysis (New York: Wiley, 1958), Chaps.8-12

3. Zvi Griliches, "Research Costs and Social Return: Hybrid Corn and Related Innovations," Journal of Political Economy, October 1958, pp. 419-431

In this respect a better prototype is A. W. Brown's study of economic benefits attributable to the development of atomic absorption spectroscopy by the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO).[1] Brown identified more than a dozen applications for a new and more efficient spectrometer and, to estimate the benefits from these diverse applications, he interviewed some 37 different user organizations. An equally extensive interview schedule would undoubtedly be necessary to assess with tolerable precision the benefits from a typical NASA contribution. Even then, many NASA cases would pose special difficulties because they involve know-how and techniques not directly embodied in hardware, whereas Brown was able to devote his analysis to a single well-defined instrument.

2. Assessing NASA's Share of the Benefits

More fundamental conceptual problems must be solved in estimating how much of the benefits of an advance one can attribute to a NASA contribution. The crux of the matter is that few technological advances of any importance originate through the efforts of only a single person, group, or organization. Rather, numerous groups are likely to be at work on various aspects of the technology in a complex interacting way. This process can be illustrated with a well-known example in the field of nuclear physics. The basic experiment through which Otto Hahn and Fritz Strassmann discovered nuclear fission in late 1938 had been performed previously by Enrico Fermi in Rome during 1934, by Irene Joliot-Curie and associates in Paris during 1937 and 1938, and was being prepared by Philip Abelson at Berkeley when the nuclear age dawned. Knowledge flowed freely among the several research teams, influencing hypotheses and experimental design. In this multiple-paths environment, it seems fair to say that if Hahn and Strassmann had not achieved their momentous insight when they did, someone else surely would have done so later, and in all probability not much later.[2] Similar parallelism occurred in the experimental proof that chain reactions were possible and in the conception of isotopic separation methods. For instance, the gaseous diffusion process using uranium hexafluoride was outlined almost simultaneously and independently by George Kistiakowski in the United States and Franz Simon in England.

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1. A. W. Brown, The Economic Benefits to Australia from Atomic Absorption Spectroscopy," The Economic Record, June 1969, pp.158-180.

2. See F. M. Scherer, "Was the Nuclear Arms Race Inevitable?" Co-Existence, January 1966, pp. 59-69.

Examination of the NASA contributions suggests that, like Hahn and Strassmann, NASA has typically not been working alone in the new fields of technology where it has made contributions. Instead, there was usually parallel and prior work sponsored by other federal government agencies, private firms, universities, and/or research institutes. For purposes of the present study, the key methodological question was, how should the credit be divided up among the several contributors?

This problem would require the use of marginal analysis, supplemented by network theory. The simplest theoretical illustration is the case of multiple research groups working in parallel, but independently, on a problem, with each group having, say, one chance in twenty of solving the problem during any given year's activity. Given these assumptions, the contribution of an additional equally competent and lucky research group can be evaluated through straightforward probability analysis. Thus, it can be shown that if four hypothetically identical groups are working in parallel and if a fifth path is added to the network, the average expected time from start to successful solution is reduced from 5.39 years to 4.42 years. In this case, the economic benefits from the 0.97 year speedup are correctly attributable to that fifth group, even though some other group turns out after the fact to have "won" the race, since *ex ante* a resource-allocating decision-maker could not have foretold which group would have been lucky enough to find the solution first.

To be sure, this illustration grossly oversimplifies reality. The typical real-world case characteristically involves an extremely complex network. If the network for some particular contribution process could be specified at least approximately, it would be possible to simulate the network on a computer, adding and withdrawing paths, modifying demand levels and hence resource allocations, etc., to determine how the presence or absence of a contributor like NASA affects the rate or character of technological progress. There is no reason why such an undertaking would not be feasible. Indeed, a group of British economists did some modest exploratory research in this direction.[1] Still the voids in our knowledge of the nodal functions and the interaction effects are so great that a major research effort would be required merely to estimate the network relationships for a single, relatively simple, technological advance. Even then, a high degree of quantitative precision could not be expected from such a pioneering venture. Such a venture was obviously beyond the scope of the study.

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1. I. C. R. Byatt and A. V. Cohen, *An Attempt to Quantify the Economic Benefits of Scientific Research*. London: United Kingdom Department of Education and Science, 1969.

B. Subjective Assessment

Given these difficulties in quantitatively assessing the impacts of various contributions on the advancement of a development, two subjective approaches were developed. The first was a simple subjective assessment of the actual and potential impact of each contribution on a linear scale of high, moderate and low. The second was a case study approach, describing the economic impact of several major technological advances on a particular development and tracing NASA's role in helping to bring about those advances. The scalar approach is described below, while the case studies are contained in section IV of this report.

The impact of a NASA contribution on the advancement of a major development was defined as the effect the contribution had on the development itself or on the environment in which the development exists. That is, did the contribution bring about a positive change? Four types of impacts were assessed:

- Technological impact. The affect a contribution has in changing the matrix of products, processes, techniques, methods and materials that make up the development.

- Scientific impact. The affect a contribution has in changing what we know or how well we understand the basic phenomena related to a technological development.

- Economic impact. The affect a contribution has in changing the economics of the development or the economics of the system in which the development is applied, including the availability and cost of the technology that makes up the development.

- Social impact. The affect a contribution has in changing the immediate social environment in which the development exists. (For the purposes of this study only first-order or primary social impacts were included.)

In interviews, NASA scientists, engineers and administrators were asked to subjectively assess the impact of their own contributions and the NASA contributions with which they were most familiar. Using a linear scale of 1 for high, 2 for moderate and 3 for low, an assessment was made for each contribution in each of the above four categories (technological, scientific, economic and social) for both actual (present) and potential impact. Each NASA assessment was reviewed by two members of the project team. In those cases where a NASA assessment of the impact of a contribution could not be obtained, the assessment was made by the analyst on the project team responsible for that particular field of technology. These judgements were, in turn, reviewed by another member of the team.

Weighted averages for actual and potential impact were calculated for each field, in each of the four categories. Actual impact represents impact that has already been realized to date from the NASA contributions while potential impact represents the total impact of the contributions to be realized. Using potential impact as a measure of total impact to be realized does not mean to imply that the estimated total impact will definitely occur, since these are estimates of potential that might never be realized. Nevertheless, the assessment of impact already realized (actual) versus total impact (potential) is an important concept since it reveals much about the time lags experienced in applying NASA technology to nonaerospace needs.

Impacts of the NASA contributions, averaged for all twelve fields by category of impact, are shown in Figure 1. The technological impact of NASA contributions is greatest, followed by economic impact, scientific impact and social impact.

Technological impact of NASA contributions, by fields of technology, is shown in Figure 2. The technological impact does not appear to vary too greatly between fields, with assessments ranging from moderate to moderate to high. NASA contributions had the highest technological impact upon the field of telemetry and the lowest on integrated circuits.

The scientific impact of NASA contributions, shown in Figure 3, appears to vary much more by field of technology, with NASA having a very low impact on some fields such a machinery and joining, and a moderate impact on others such as microwave systems and internal gas dynamics.

Economic impact assessments, shown in Figure 4, ranged from telemetry with the highest potential economic impact of those studied, to energy conversion with the lowest potential impact.

The direct social impact of NASA contributions varies greatly between fields studied, as shown in Figure 5. For most fields, NASA's contributions have low social impact. For some other fields, however, such as gas dynamics, simulation, and telemetry, the impact of NASA's contributions approach moderate.

Figure 1. Impact of NASA Contributions on Major Developments in 12 Selected Fields of Technology

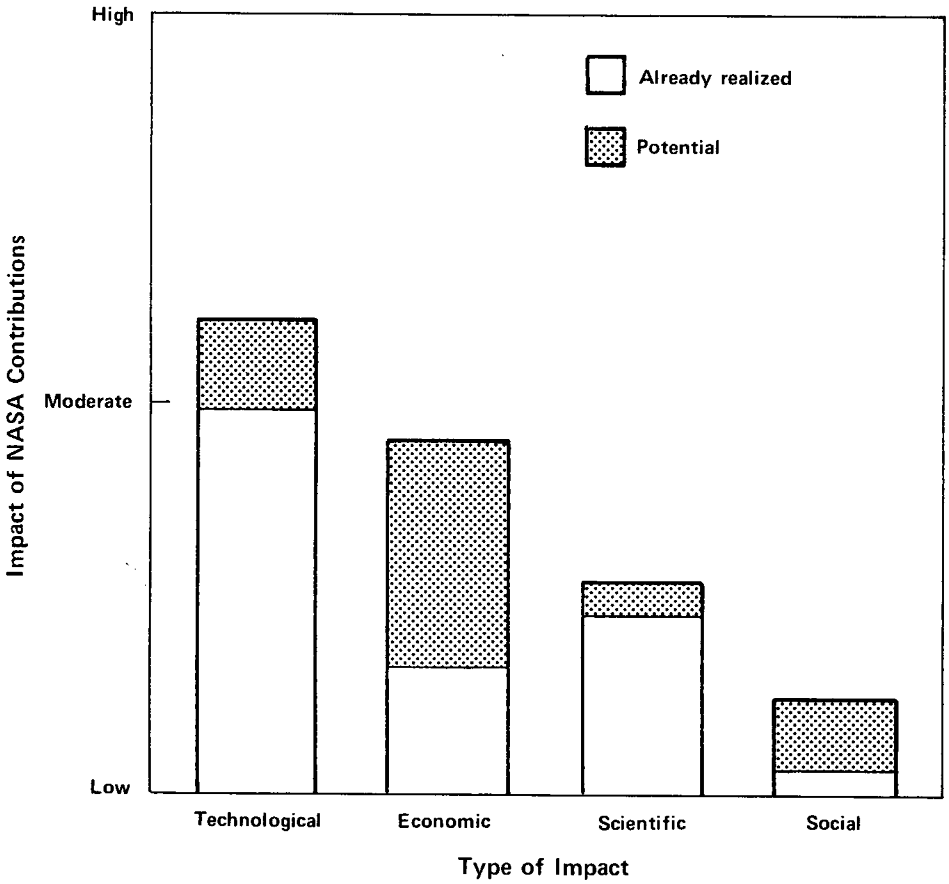


Figure 2. Technological Impact of NASA Contributions on Major Developments in Selected Fields of Technology

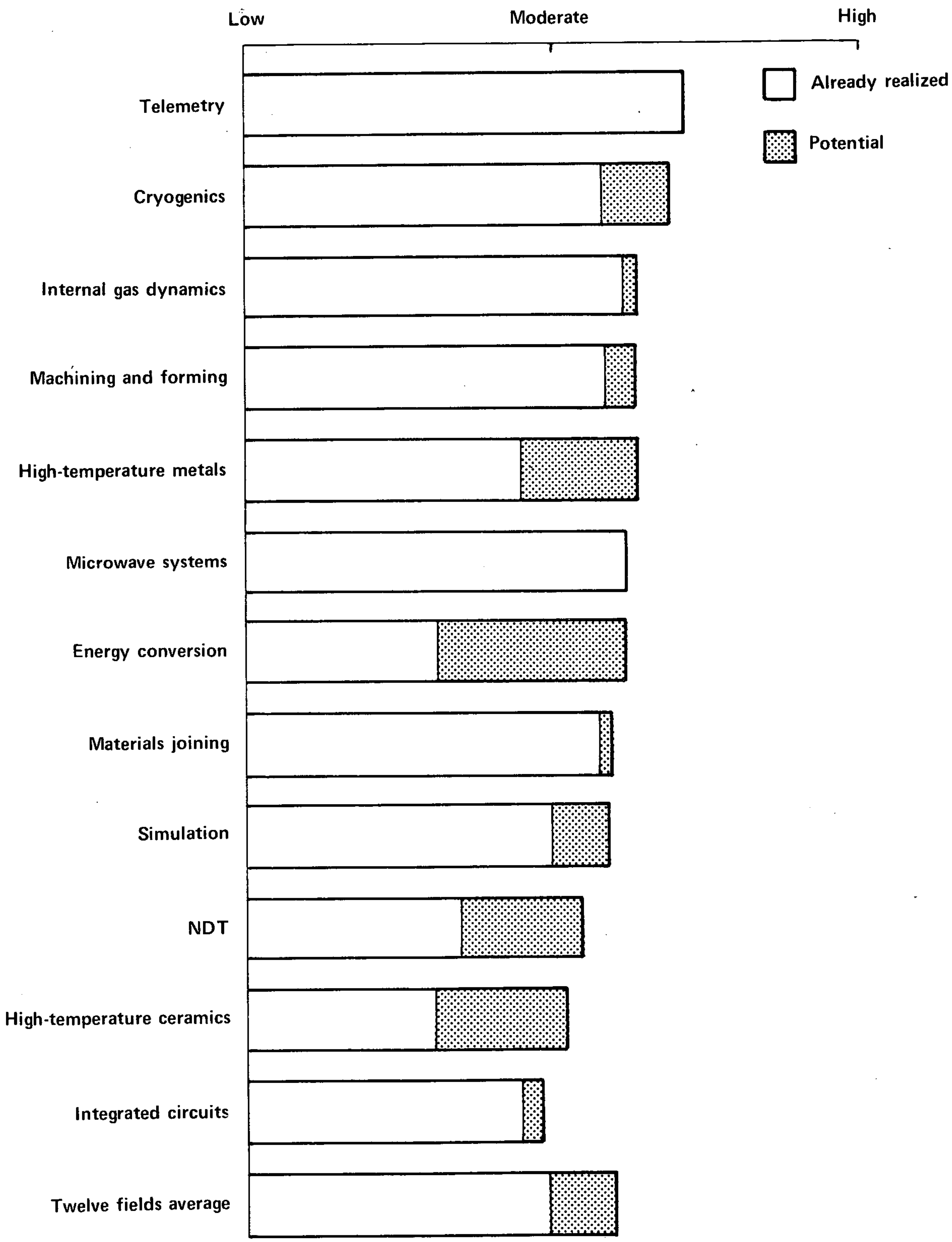


Figure 3. Scientific Impact of NASA Contributions on Major Developments in Selected Fields of Technology

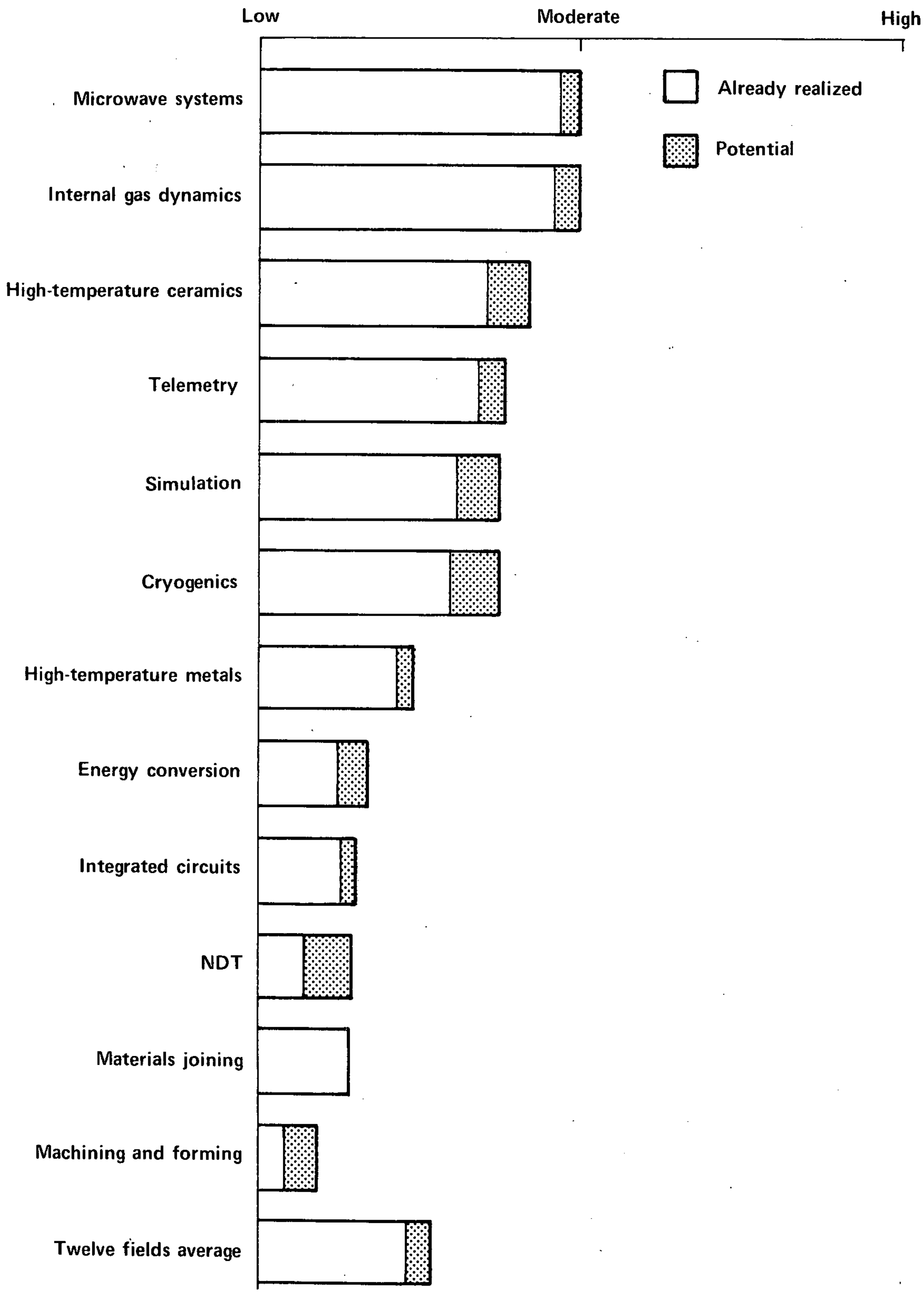


Figure 4. Economic Impact of NASA Contributions on Major Developments in Selected Fields of Technology

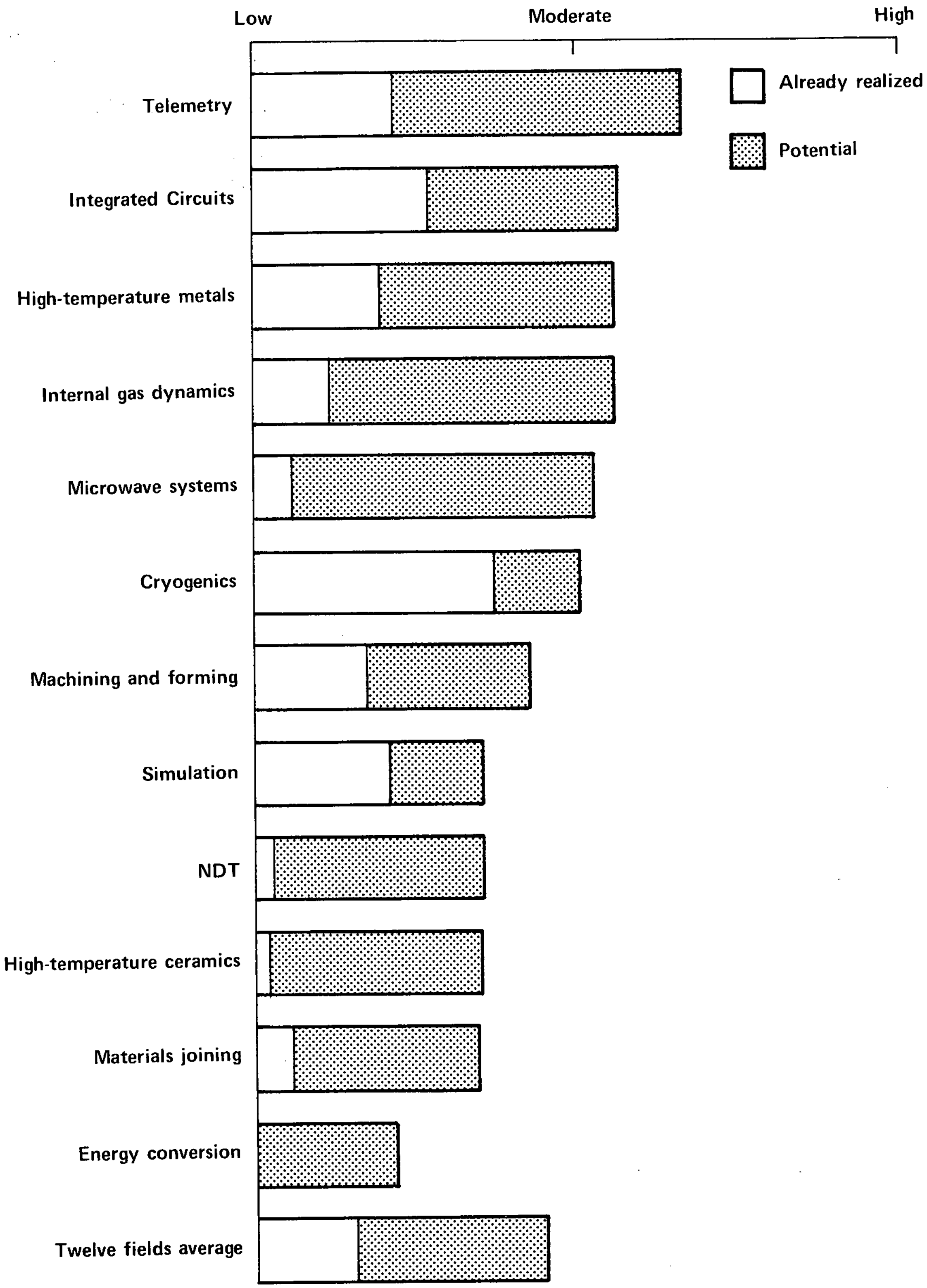
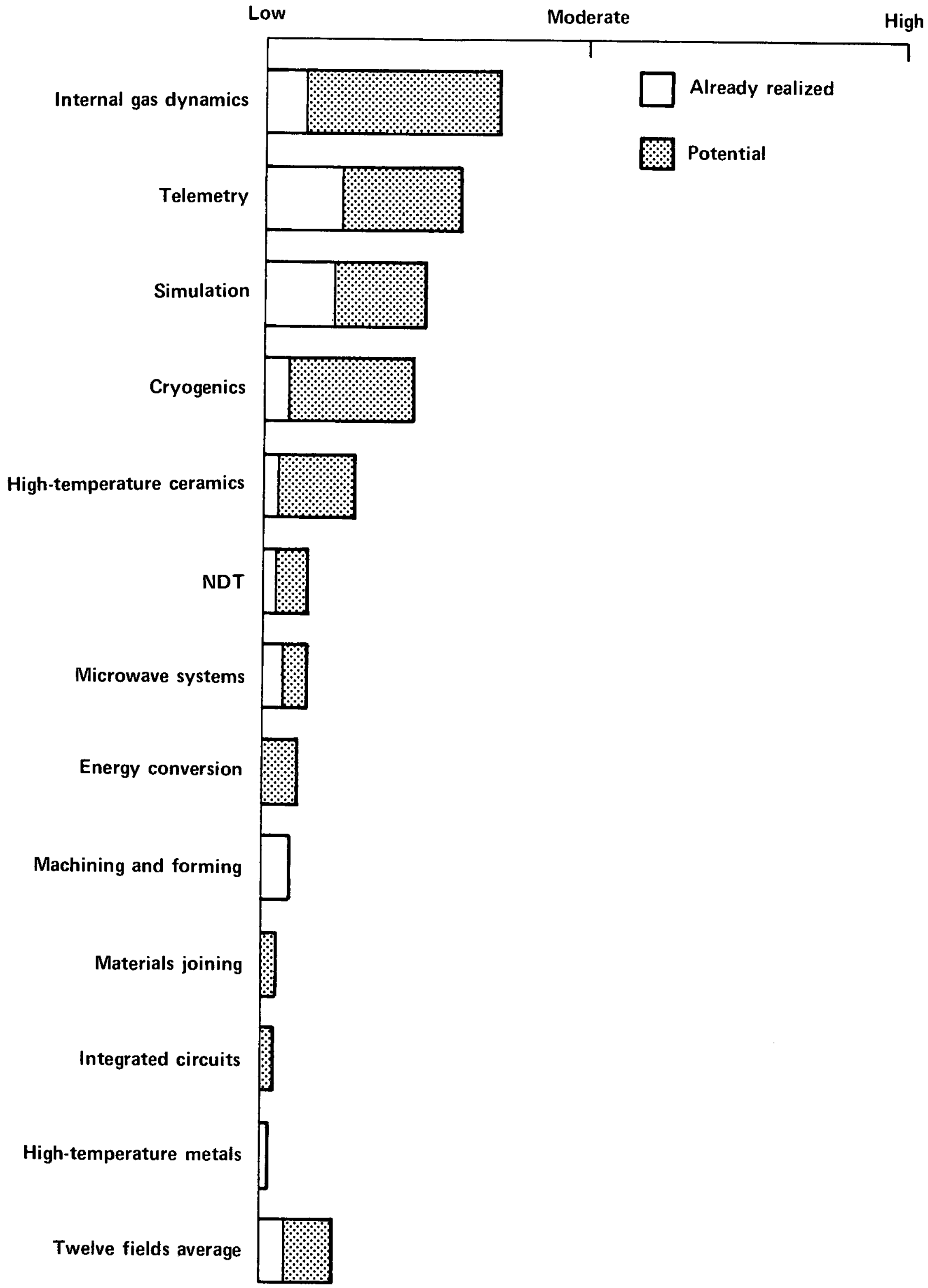


Figure 5. Social Impact of NASA Contributions on Major Developments in Selected Fields of Technology



Impact of the NASA contributions also varies with the level of technological change brought about by the contribution. As expected, class I contributions have a greater impact than class II contributions, and class II contributions have a greater impact than class III contributions. This was true for each of the individual fields as well as for the twelve fields combined, as shown in Figure 6.

Taking the assessments of actual and potential impact for each field, the extent of impact already realized was determined by calculating the ratio of impact felt to date (actual) to the total impact to be realized (potential). For all twelve fields, almost all of the total scientific impact of the NASA contributions has already been realized (90 percent) as has the technological impact (70 percent). This is understandable in light of how these types of impact are effected. That is, the scientific and technological impact of a contribution starts to be felt when the contribution is still in its early stages of development. Economic impact on the other hand, is much more dependent on the application of the contributions. The fact that only 30 percent of the total economic impact of the NASA contributions to the 12 fields has been realized to date indicates a lower level of application. In the same way only 30 percent of the potential social impact of the NASA contributions has been realized to date.

The relationship between the economic impact and rate of application was examined for each of the fields, and is shown in Figures 7 and 8.

Data on economic impact already realized for each field was calculated as described above. Figures on aerospace and commercial applications were calculated from data collected on each NASA contribution.

Using least squares regression analysis, there appears to be a valid correlation between economic impact and rate of application. This is as expected, and indicates that even when a sizeable proportion of NASA contributions are finding aerospace applications, the percentage of economic impact realized is relatively low. With almost 55 percent of the NASA contributions being applied in aerospace, only 30 percent of the economic impact has been realized (Fig. 7). Economic impact realized rises more sharply as NASA contributions find commercial applications (Fig. 8). However, with less than 25 percent of the contributions being applied commercially, it is not surprising that the amont of economic impact felt to date is only a small proportion of its total potential.

Figure 6. Impact of NASA Contributions on Major Developments in Twelve Fields of Technology for Different Classes of Technology

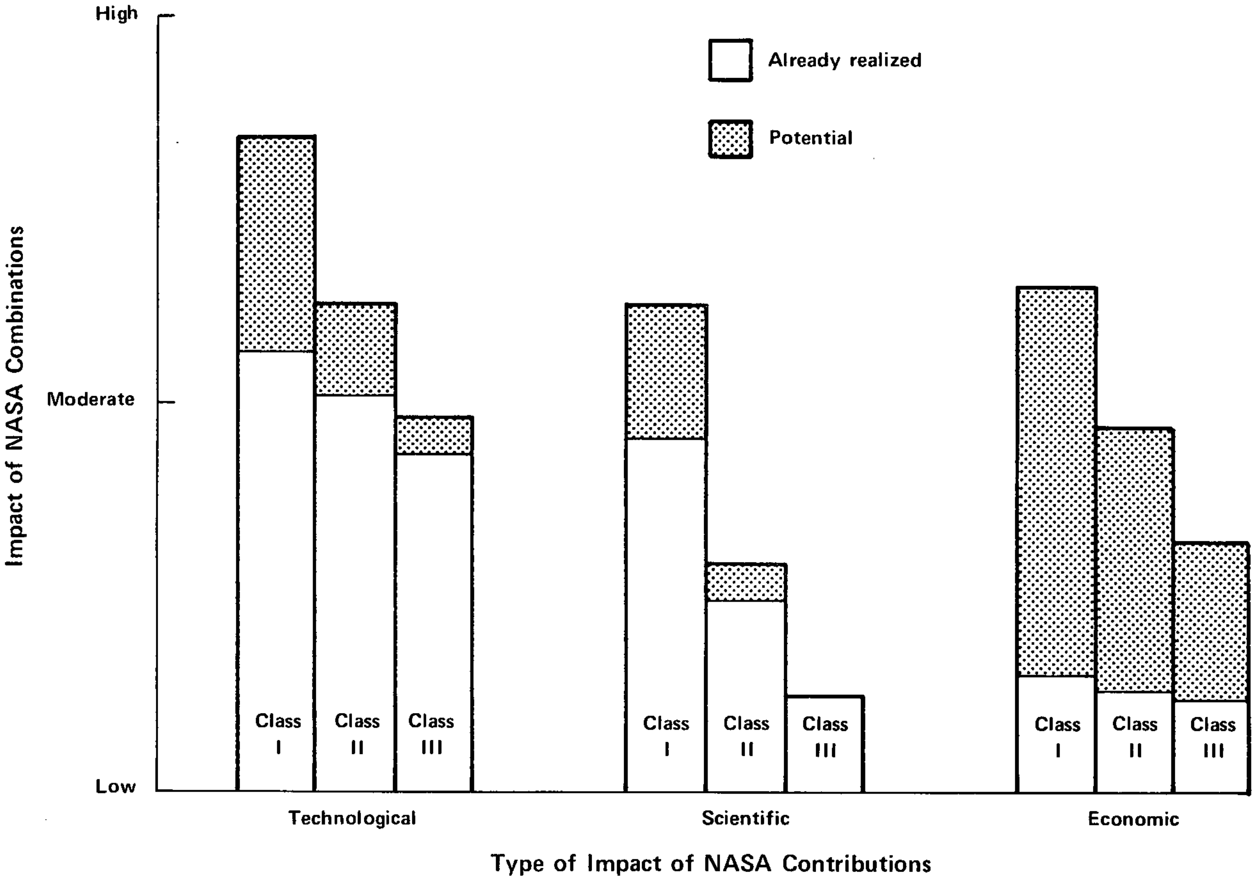


Figure 7. Relationship Between Economic Impact Already Realized from NASA Contributions and Proportion of Contributions Finding Military or Aerospace Applications

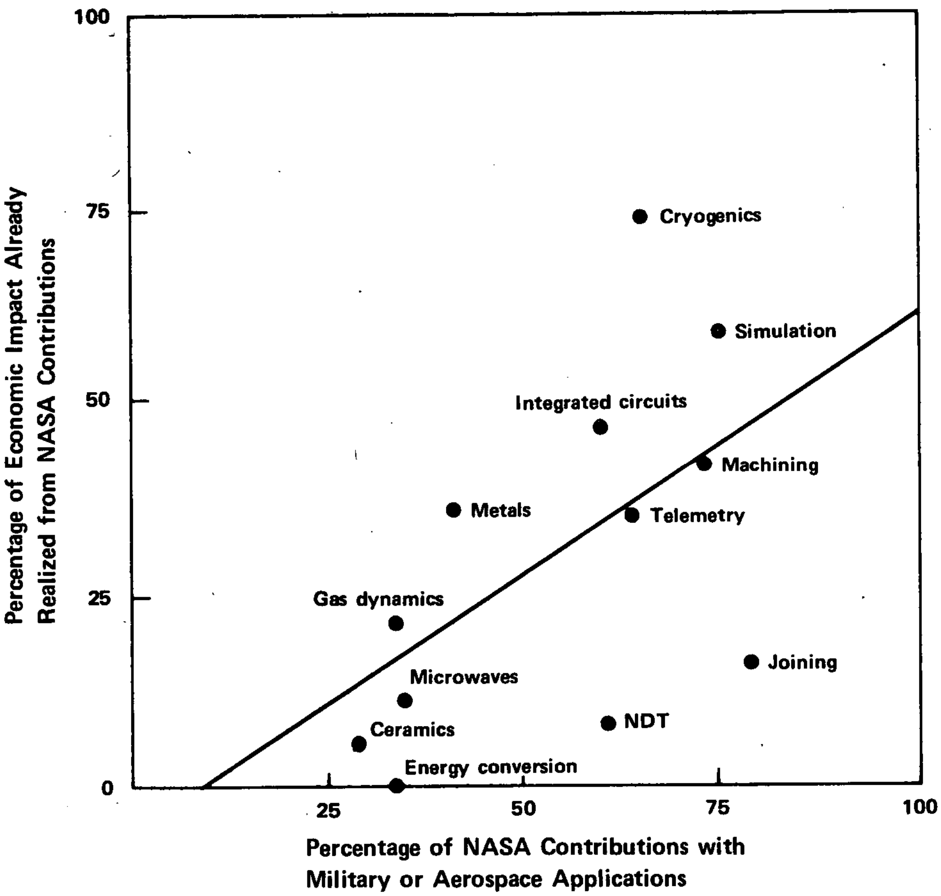
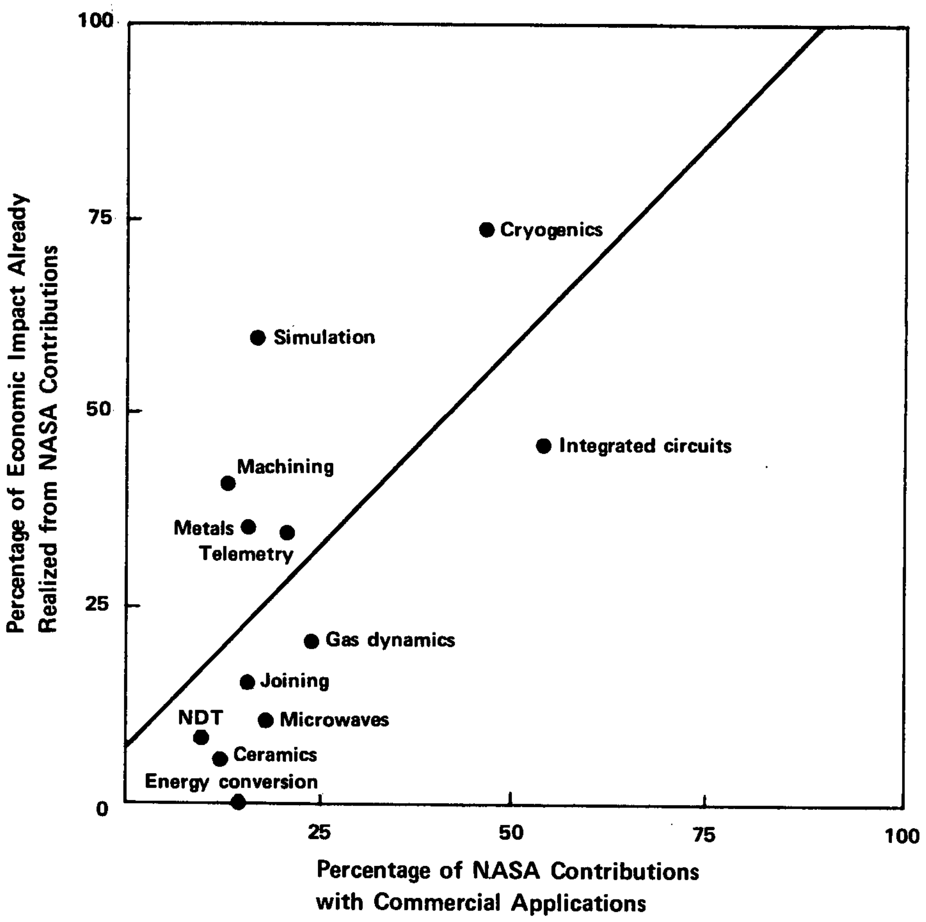


Figure 8. Relationship Between Economic Impact Already Realized From NASA Contributions and Proportion of Contributions Finding Commercial Applications



A similar analysis determined that a correlation did not exist between technological impact and applications rate. This indicates, as stated earlier, that the technological impact of contribution might start to be felt much earlier in the life cycle of the contribution, during research or advanced development, and a good part of its total impact is probably already realized by the time the contribution starts to find widespread application.

IV. CASE STUDIES OF THE ECONOMIC IMPACT OF TECHNOLOGY

Due to the difficulties in quantitatively assessing the economic impact of NASA contributions, a case study approach was decided upon. Selected cases can be used to demonstrate the extent of economic impact and the pervasiveness of the NASA contributions. Four cases were selected for this study. They include: (1) energy and the gas turbine; (2) nickel-cadmium batteries; (3) improved stability of MOS transistors and integrated circuits; and (4) high-power microwave transistors.

A. The Case of Energy and the Gas Turbine.

The energy outlook for this country during the next 30 years is characterized by a noticeable degree of uncertainty. Recently, the trend has been in the direction of increasing use of energy as a component of economic output. However, concern with the environmental implications of expanding energy consumption and changing technology may temper energy growth. One fact though, does seem certain: the most recent rate of growth in consumption of electrical energy cannot be sustained indefinitely. Currently, consumption of electricity in the U.S. is doubling approximately every eight years, representing a compound growth rate of 9 percent. Historically, however, the growth in total energy production has only been about 3.5 percent or a doubling time of 20 years. Assuming continuation of the 9 percent growth of electrical energy and the 3.5 percent total energy growth, by the year 2000, electrical energy would "capture" the entire U.S. energy market. However, given present indications, the prospects of a total electric energy economy occurring during the remainder of this century would seem to be a most unrealistic assumption.

While caught in the dilemma of planning for long-term growth, the power industry has been confronted with the immediate problem of satisfying a highly variable, daily load requirement. To accommodate these daily load variations, equipment has to be added that can operate both discontinuously and for relatively short periods of time. Most generating systems are designed to meet these so-called peaking loads. However, serious operating difficulties can be encountered if the load on high-pressure, high-temperature steam turbines is varied rapidly, as would be the case in a peaking situation. There must be some flexibility in the choice of facilities that will carry the peak of the load. Most experience has shown that overall system economics rather than the specific suitability of particular forms of generation should be the determining feature.

In addition to using the conventional means of generation, pumped storage plants, diesel engines, and gas turbines have been used quite successfully to meet these peak loads. One of the newer means of power generation, the gas turbine generator, has demonstrated its suitability as a source of economical peaking and emergency power.

Several features that have enhanced its suitability for this purpose are its low initial costs, rapid start-up, locational flexibility, and automated characteristics.

The development of the gas turbine as a source of power demonstrates the use of equipment, originally serving commercial and military transportation needs, for an application unrelated to the original purposes. Because of its early applications, it would not be unexpected to find that various military and civilian governmental agencies were heavily involved in the early research and development of the gas turbine engine. Also, building on their original experience, these groups have continued their involvement to the present time. Through the 1930's and 1940's, the military and the National Advisory Committee for Aeronautics (NACA), through a heavy involvement in aircraft design and propulsion, were the leaders in the effort. When NACA was reorganized into NASA in the late 1950's, priority changes de-emphasized research and development on the gas turbine. However, in recent years NASA has shown renewed interest in gas turbine technology. The current emphasis is on modification and improvement rather than any radical departure from the basic equipment design.

Within the total U.S. energy picture, the gas turbine has come to occupy a specialized role in both propulsion and electric generation. A measure of the gas turbines' importance is the current dollar sales figures for both categories of use. The total value of shipments of aircraft engines and parts in 1970 was $5.5 billion, with approximately two-thirds attributable to gas turbine engines. The United States military has been a significant customer, with approximately 25 percent of the purchases. Total value of exports of gas turbine engines and parts in 1970 was in excess of $250 million. Current estimates place total sales on the nonaircraft turbines at $500 million, with the electric utility industry as the largest purchaser.[1]

1. Gas Turbine Development

Power generation uses are the largest component of the nonaircraft market for gas turbines, currently accounting for approximately 80 percent of the sales. One of the best known uses of gas turbines has been in "total energy" applications. The "total energy" concept means that gas turbines are used to generate electric power and that the by-product heat is used for heating in the winter in heat exchangers and for air conditioning in the summer. Hotels, schools, and shopping centers are typical examples of such applications. Other current applications are transportation (truck and railroad), marine propulsion, gas pipeline pumping, and direct mechanical drive. All of

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1. Gas Turbines - The Coming Revolution in Industrial Power. New York: Institutional Research Dept., Oppenheimer & Co., 1971.

these applications, including power generation, use a modified version of the gas turbine engine that was developed originally for aircraft propulsion purposes. Since the nonaircraft turbine evolved directly from the aircraft version, all developmental work that originally went into aircraft turbines ultimately contributed to the usefulness of gas turbines in the newer applications.

The major contributors to the advancements in the gas turbine engine field have been the Air Force, NASA, and the large engine manufacturers such as General Electric, Pratt and Whitney, and the Allison Division of General Motors. Between 1958 and 1965, when the newly formed NASA shifted emphasis from an aeronautical mission to a space mission, much of the advanced work that had originated at NACA, traditionally the technical leader in gas turbines, was exploited by private companies. Many of the gas turbine engine advances of the 1960's were an outgrowth of the NACA work done in the 1950's.

2. Technical Advances in Nonaircraft Turbines

Use of gas turbine engines for stationary electric power generation has been limited to peaking power and emergency standby applications. The turbines have been "locked into" these applications by their relatively low thermal efficiency in comparison to fossil-fuel steam-electric power plants. However, dividends are accruing from the extensive research and development efforts on military and commercial aircraft applications. Specifically, the result of these efforts has provided the basis for projecting substantially improved, large-capacity, base-load gas turbine power systems. These systems have significantly higher thermal efficiencies than those attainable with present systems. Part of the effort going into a study of advanced power cycles and nonpolluting fuels has provided some projections of the anticipated rate of progress of gas turbine technology during the next two decades. The study concludes in its analysis of open-cycle gas turbine power systems that the introduction of aircraft gas turbine technology into base-load gas turbines will allow significant improvements in performance. Also, advanced-cycle gas turbine power systems will become likely sources of base-load electric power.[1]

A revealing indicator of the long-term trend in heat rates, shown in Figure 9, is the historic heat rate improvement for fossil steam,

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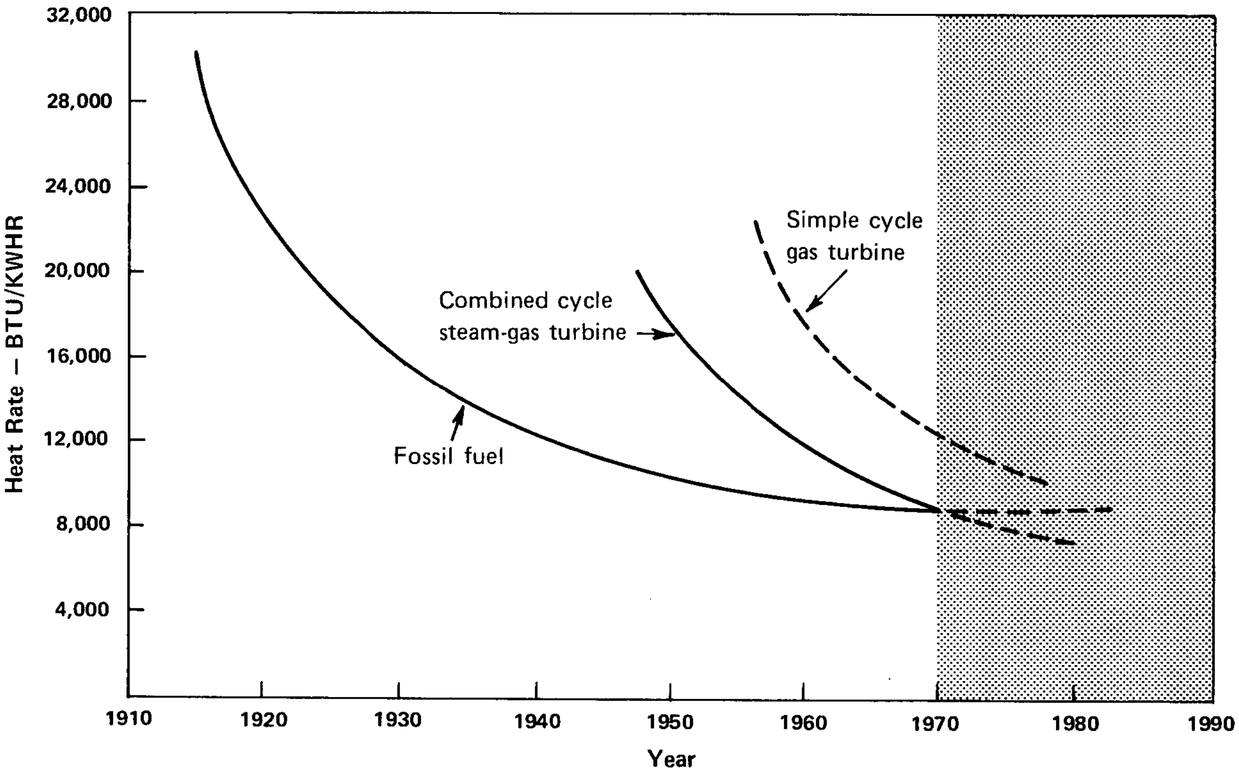
1. Robson, F. L., et al., Technological and Economic Feasibility of Advanced Power Cycles and Methods of Producing Nonpolluting Fuels for Utility Power Stations. Hartford, Conn.: United Aircraft Research Laboratories.

Figure 9. Historic Heat Rate Improvement for Fossil Steam, Simple Cycle and Combined Cycle Gas Turbine Units



Source: Gas Turbine Handbook; Sawyer's Gas Turbine Catalog; "Gas Turbine Applications in the U.S. Utility Industry." H.L. Lokay and G.E. Seglem, ASME Paper No. 70-GT-71.

simple-cycle, and combined-cycle gas turbine units.[1] The more interesting trend, though, is that in recent years technology appears to have exhausted the possibility of any further significant reduction in heat rate for straight fossil fuel generation. This contrasts markedly with combined and simple-cycle turbines where the trend is obviously shown to be still declining.

Projecting where technology may be heading and at what rate is certainly not without serious limitations. However, in the case of the gas turbine, the stated aim of improved efficiency dictates where the focus of research will be directed and, therefore, in what areas the probability of success is highest. In the report on advanced power cycles and nonpolluting fuels, a significant conclusion was made in regards to technology projections:

> Existing differences between design philosophies of industrial gas turbine power plants and aircraft gas turbine propulsion systems will diminish as a result of continuing efforts to improve thermal efficiency. Significant improvements in specific horsepower (hp/lb-sec of engine airflow) and thermal efficiency for simple-cycle gas turbines can be achieved only by increasing turbine inlet temperature and compressor pressure ratio, since turbomachinery component efficiencies have reached a relatively high level due to over 30 years of extensive research and development on compressors and turbines for aircraft propulsion.[2]

3. Specific Areas of Technological Advance

There are several areas of technological advancement in the field of gas turbines in which NASA played a major role in advancing the technology. Among these are increased pressure ratios, turbine cooling techniques, turbine materials and coating technology.[3]

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1. A combined-cycle plant is basically a simple-cycle operation that takes the exhaust gases that would normally be expelled into the atmosphere and uses them instead to produce steam from a waste heat boiler.

2. Robson, F. L., loc. cit.

3. Although emphasis is on developments that NASA had a major role in advancing, it should be remembered that there were numerous other contributions and contributors that advanced the state of technology to make possible any particular development.

Increased pressure ratios. Because of its influence on the overall performance of gas turbine power plants, increasing the pressure ratio has been a major area of continuing investigation by the engine manufacturing companies. The overall improvements in compressor component performance, mainly through the R&D efforts on aircraft turbine engines, have been chiefly responsible for increasing the pressure ratios. Compressors designed in accordance with aircraft technology exhibit an average stage pressure ratio of 1.29 per stage, whereas their industrial counterparts, designed with moderate blade loadings and rotative speed, develop an average stage pressure ratio of 1.12 per stage.[1] Since the present levels of compressor efficiency are relatively high, current aircraft compressor research efforts are directed primarily at increasing stage pressure ratios without sacrificing efficiency.

The technological advances that have affected compressor pressure ratios are the results of research into improving aircraft compressor pressure ratios. The apparent trend seems to indicate that the technology is becoming available that will allow the eventual introduction of machines with pressure ratios exceeding 30. This will certainly be a prerequisite feature for the high-efficiency, base-load gas turbine cycles which are anticipated for the decade of the 1980's.

Even though there may be some question about the feasibility of transferring future results of aircraft turbine research on higher pressure ratios to nonaircraft turbines, there is no question about the historic benefit of the effort. NASA's contribution to this effort has certainly been significant. Much of the fundamental technology to increase the pressure ratio was advanced by NACA programs during the 1950's. These advances were achieved primarily through research contracts with the major engine manufacturers. Since becoming reinvolved with turbine technology in 1966, the NASA Fan and Compressor Technology Program at Lewis has aimed at increasing the pressure ratios per stage, while maintaining acceptable efficiency and operating range. This would permit a reduced number of stages for a given application resulting in lighter and more compact fans and compressors. Although no single specific contribution can be classified as particularly significant, there have been numerous incremental contributions, such as a simple method for improving stall conditions in rotor blades, that have benefited gas turbines.

Turbine cooling. Since significant increases in the operating efficiencies of gas turbines can be realized through increasing the operating temperatures, intensive research is being conducted toward

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1. Selected Technology for the Electric Power Industry. Washington, D. C.: National Aeronautics and Space Administration, September 1968 (SP-5057).

cooling turbine blades and vanes to withstand the high inlet temperatures. At the present time, the requirements for cooling contemporary industrial gas turbines are not as demanding as are being contemplated for the next generation engines. Only first-stage vanes and disks of current advanced-design industrial gas turbines are cooled. However, it will be necessary to cool succeeding stages of turbine blades and vanes, that will be operating at temperatures of 1,800°F. and above, in future turbines for base-load electric power generation.

Cooling is an extremely important parameter that bears most heavily on the actual operating efficiencies that can be obtained through higher inlet temperatures. For every degree of temperature gained through technical advances, an extra 100 pounds of engine thrust is produced. Also, the use of cooling permits increased allowable stress levels that improve the reliability of the turbine itself. All of these features are immediately translated into expanded component life and reduced replacement costs.

NASA had an early involvement in cooling research. An entire section at NASA-Lewis Research Center (LERC) was devoted exclusively to this field of technology. However, with the change in objectives in the latter 1950's, the group discontinued its work. Many of the contributions of this early effort provided the basis for the advances achieved by engine manufacturing companies in the 1960's. In 1966, LERC's Turbine Cooling Section was reactivated. At the present time, they are engaged in investigating turbine cooling for applications to aircraft gas turbine engines at gas temperatures up to 4,000°F. and gas pressures up to 600 psia.

Turbine materials and coating technology. High temperatures, extreme variations in corrosive environments, high mechanical strength, light weight, and cost are major considerations of the gas turbine designer. These requirements have created an increasing demand for new materials. Alloys with increased high-temperature strength have been developed, along with coating materials to protect these alloys.

Early NASA work demonstrated the feasibility of using fiber-filled material to attain increased structural strength. Since 1965, extensive NASA efforts have been directed at developing a better understanding of mechanisms for improving the structural properties of metals and composites for high-temperature applications.

4. Future Role of the Gas Turbine in Power Generation Systems

The aircraft derivative turbine's growth should not be hindered by an inadequacy in technological advancement. The critical determinant of turbine use will be the long-term planning of the electrical utility industry with respect to how they incorporate the gas turbine into their generating systems. If the past is a valid indicator of acceptance of turbine equipment, there should be little question about a growing role in the future.

On a world-wide basis, electrical power generating capacity in gas turbines, as shown in Figure 10, increased from some 2,500 Mw in 1961 to approximately 33,000 Mw in 1970.

In 1956, the installed capacity provided by gas turbines was less than 1,000 Mw. In the same year, the world electric generating capacity was estimated at 382,505 Mw.[1] By 1970, as shown in Figure 11, the United States gas turbine capacity alone had increased to 16,500 Mw. This represents approximately half of the world total capacity in the gas turbine prime mover. The percent of generating capacity from different sources in the United States is shown in Table 5.

As of December 1969, fossil fuel steam turbines accounted for some 78 percent of total capacity. Gas turbines accounted for 3.2 percent of total. The new additions estimated during the 1969-1978 period by the Edison Electric Institute list steam turbines at 58 percent, nuclear at 28 percent, and gas turbines at 5.3 percent.

Forecasting future U.S. energy and electric power growth for the next decade is a difficult task. To estimate the generating components of that growth is even more challenging. However, Westinghouse has recently estimated that U.S. utilities would have to build more than 1,000,000 Mw of new capacity in the next twenty years. Such an expansion would nearly triple the present installed capacity of roughly 300,000 Mw. Half of the new capacity increase (500,000 Mw) will be needed to handle the anticipated increase in base-load, and 75 percent of the new capacity will be in the form of nuclear facilities. Westinghouse further estimates that 400,000 Mw of the new capacity will be needed to meet the growing intermediate load (which coincides with the load added roughly between 7:00 a.m. and midnight by the activity of people at home and at work), and a sizable fraction of that will be provided by gas turbines. The new peaking capacity, amounting to an estimated 170,000 Mw, will be divided in the following manner: gas turbines and pumped storage in the ratio of 10 to 7.[2]

Increased consideration is being given to combined cycle plants for new intermediate or 25 to 50 percent capacity factor generation applications. Plant installed costs are expected to be near $100/kw and net plant heat rates below 9,500 Btu/kwh. At least one plant in the 150 to 200 Mw range is planned for operation, and several are under consideration at this time. In the 50th Semi-annual Electric

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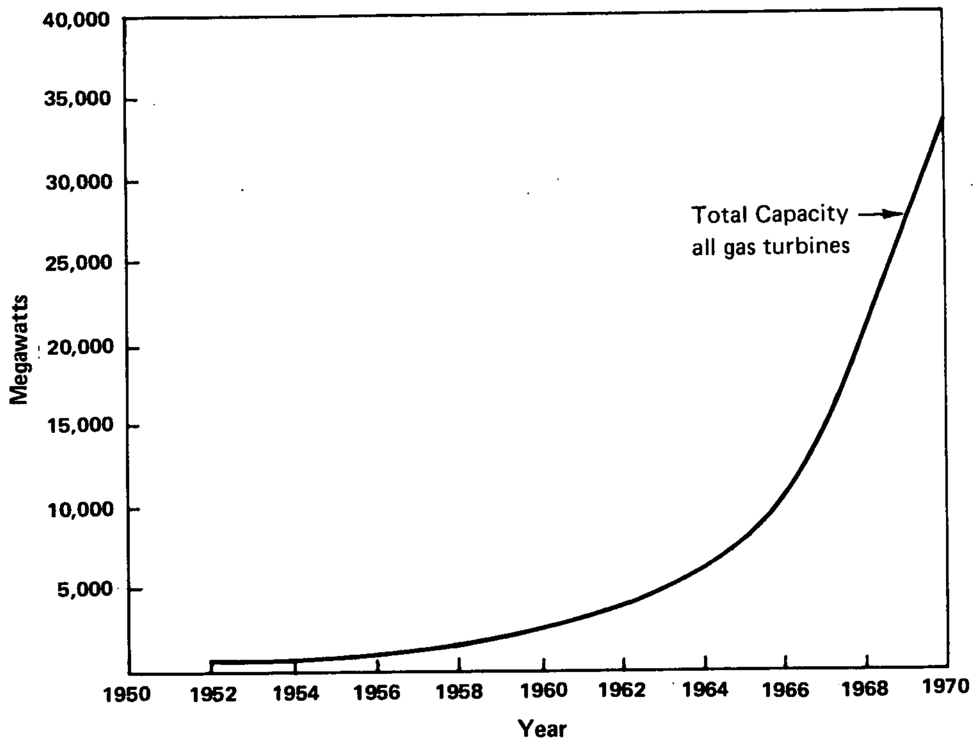
1. "Gas Turbines in Utility Power Generation," Special Report, Gas Turbine International, Jan-Feb. 1971.

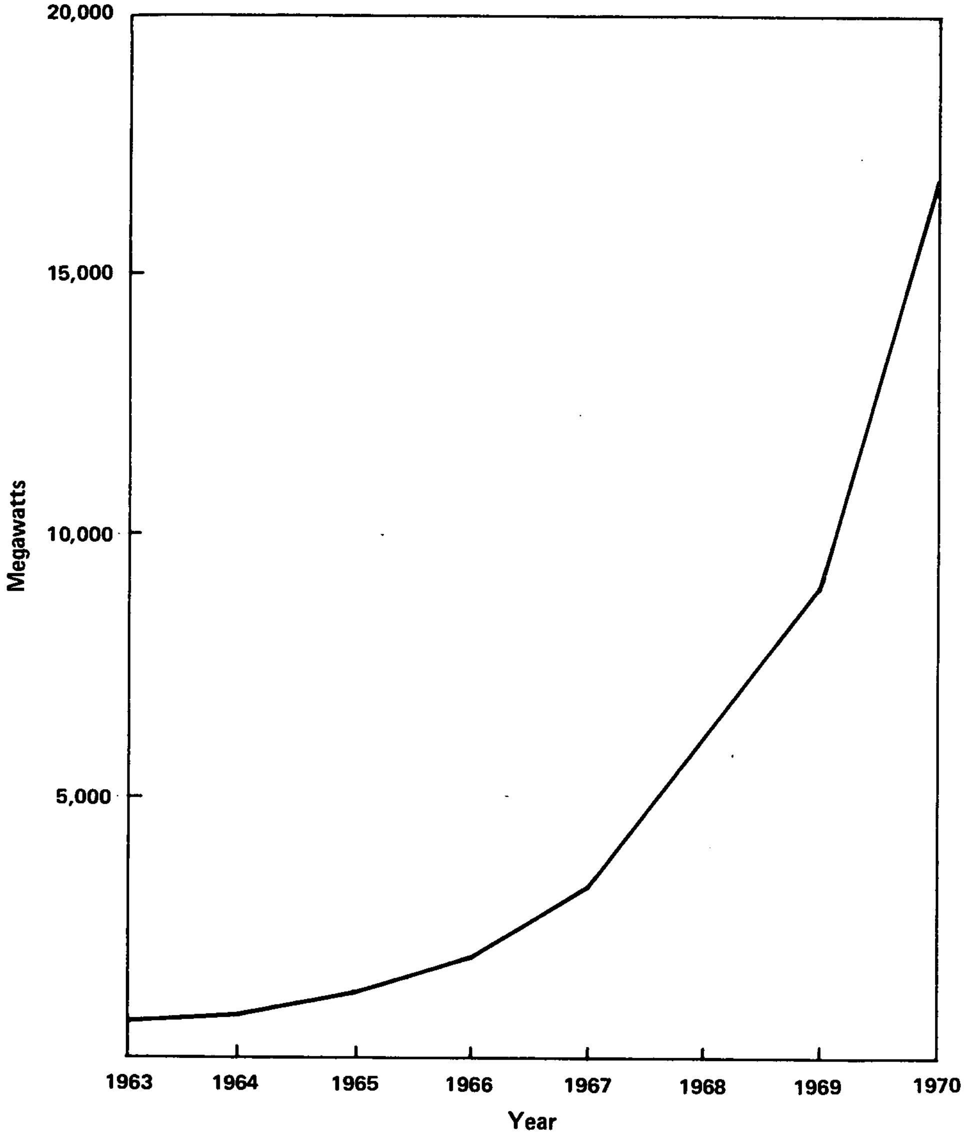
2. "The Conversion of Energy," Scientific American, Sept. 1971.

Figure 10. Worldwide Gas Turbine Electrical Power Generating Capacity



Source: "Gas Turbines in Utility Power Generation," *Gas Turbine International,* Jan.-Feb. 1971, pp. 18-31.

Figure 11. Total Installed Gas Turbine Generating Capacity in the U.S.



Source: "Gas Turbines in Utility Power Generation," *Gas Turbine International*, Jan.-Feb. 1971, pp. 18-31.

TABLE 5

UNITED STATES UTILITY GENERATING CAPACITY BY TYPES

Types	Percent Dec. 1969	Percent of New Additions 1969-78
Fossil steam turbine	78.3	58.0
Nuclear	0.9	28.2
Gas turbine	3.2	5.3
Hydro, conventional	16.1	3.1
Hydro, pumped storage	1.1	5.4
Other	0.4	--
	100.0%	100.0%

Source: Edison Electric Institute

Power Survey, the Edison Electric Institute has compiled some statistics relating to the growth in combined cycle plants. As of December 1970, 6.1 percent of total installed capacity of gas turbine equipment was in the form of combined-cycle systems. By December 1976, that figure is expected to increase to 10.3 percent.

5. Summary

Within a comparatively short period, the gas turbine has emerged from a pattern of steady growth in industrial and utility applications to develop into one of the country's fastest growth industries. At the basis of this rapid growth is the increasing demand for this prime mover by the electric utility industry. Some of these reasons for this growth have already been discussed: power outages, abnormally hot or cold seasons, the economy's rapid growth during the early and mid-1960's, and the delays in nuclear facilities.

Few energy equipment analysts see anything but a large role for the gas turbine in future years. The optimistic outlook is predicated on the demonstrated reliability in industrial service, the recent developments in power generation, and the favorable economics of this type of cycle for the utility industry. What dissent exists in this outlook lies essentially with those observers who forecast a sharp decline in shipments of turbines once "normalcy" returns to the utilities. By focusing exclusively on its most obvious attribute, i.e., a short lead-time, delivery ability which can satisfy the emergency capacity needs of a utility, these individuals ignore far more important fundamental factors affecting the economics and demand for gas turbines.

Right now, the key to the industrial gas turbine's future is the research going into advancing the technology at NASA as well as at numerous private research laboratories. A divergence in the efficiency of gas turbines versus steam turbines or diesels is developing because the gas turbine is still in the dynamic phase of its technology. This contrasts with the rather static technologies of these other two prime movers. The reason for the gas turbine's present fortuitous position can, in part, be attributed to NASA's contributions which resulted in improving the efficiency and performance of its predecessor, the aircraft turbine. Any future improvements in the aircraft version will be eventually translated into improvements in the industrial version. Therefore, this dynamic technology is the basis of the optimistic outlook for the industrial gas turbine.

B. The Case of Nickel-Cadmium Batteries.

An electrochemical battery (or, more precisely, a "cell") is a device in which the reaction between two substances can be made to occur in such a way that some of the chemical energy is converted to useful electricity. Electrochemical energy conversion devices are generally grouped into three categories: fuel cells, primary batteries, and secondary (rechargeable) batteries.

Secondary batteries, in which the chemical reaction can be reversed by applying electrical energy to the cell, are capable of being repeatedly discharged and recharged from an external source. The common lead-acid storage battery used in automobiles is the best known example of a secondary battery.

Most practical secondary batteries, other than the lead-acid system, contain an alkaline electrolyte, generally an aqueous solution of potassium hydroxide. One of the major systems in this category is the nickel-cadmium battery. Other alkaline systems are silver-zinc and silver-cadmium batteries. However, because of cost, their use is restricted almost completely to military applications.

Nickel-cadmium batteries were first developed near the end of the nineteenth century to overcome drawbacks of earlier storage battery systems. In the years since, these batteries have been highly refined, and are now produced in a wide range of sizes and in many modifications of internal construction to meet specific needs and to provide wholly new performance capabilities.

NASA has been actively involved in the improvement of nickel-cadmium batteries. Mission requirements imposed constraints of reliability, predictability, and life in excess of what was commonly available. Through extensive research, development, and testing, failure modes were identified, quality control procedures specified, and lifetimes of battery components improved. Resulting improvements in nickel-cadmium batteries have been applied selectively in commercial applications. The significance of NASA's role in nickel-cadmium battery development has been major and should continue to be so as expanding commercial applications call for higher performance and reliability. Among the NASA contributions to the advancement of nickel-cadmium battery development are efforts leading to improvements in ceramic seals, battery separators, reduced failures and more uniform and predictable performance.

Some of the more important features of nickel-cadmium batteries follow:

- Durability. In normal service the life of nickel-cadmium batteries is measured in years and in hundreds or thousands of cycles of charge and discharge.

- Minimum maintenance. Nickel-cadmium batteries do not require periodic recharging or other maintenance during idle storage at normal temperatures, although charged cells gradually lose their charge during storage.

- Flexibility. Nickel-cadmium batteries are available in a great variety of sizes and types. In size, they range from tiny "button" cells to large units for stationary and marine applications.

- Uniform voltage. Nickel-cadmium batteries deliver unusually uniform voltage during the course of discharge and can be charged at voltages only slightly higher than they deliver on discharge.

There are three major classes of nickel-cadmium batteries: vented pocket plate, vented sintered plate, and sealed sintered cell. The vented and sealed types of sintered plate form the majority of U.S. production, while the pocket plate construction is used widely in Europe. Estimates of 1969 U.S. shipments of nickel-cadmium batteries are shown below.[1]

1969 U.S. Shipments of Nickel-Cadmium Batteries by Company
($ millions)

Company	Total	Sealed	Vented Sintered Plate	Vented Pocket Plate
General Electric	8.0	5.5	2.5	-
Marathon Battery Company	8.0	3.5	4.5	-
Gulton Industries, Inc.	5.5	2.0	3.5	-
Gould Incorporated	5.0	5.0	-	-
Union Carbide Corporation	4.0	4.0	-	-
NIFE, Incorporated	3.0	-	-	3.0
McGraw-Edison	1.0	-	-	1.0
ESB Incorporated	.5	-	-	.5
Eagle-Picher Industries	.5	-	.5	-
Alkaline Batteries Corp.	.5	-	-	.5
Total	36.0	20.0	11.0	5.0

The major uses of vented pocket plate batteries are in emergency lighting, where maintenance costs are important, and in critical emergency power installations, where nickel-cadmium batteries are used as

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1. These estimates were prepared by A. D. Little, Inc., and appear in their report The Battery Industry - U.S. and International, J. H. B. George, Arthur D. Little, Inc., 1970.

starter batteries for motor generator sets. Other applications include electrical switchgear, signalling, engine cranking and power circuit breakers.

Vented sintered plate nickel-cadmium batteries are used primarily in the U.S. for engine cranking in military and business jet aircraft and for actuating cartridge starting mechanisms in the large commercial jets such as the 747 and DC-10. Other applications include high-intensity emergency lighting, portable and mobile emergency power, portable tools and equipment, engine starting, low-temperature applications and circuit breaker actuation.

Sealed-cell batteries were commercially developed after 1950 to meet a demand for storage batteries which could be permanently or semi-permanently installed in equipment and operated in all positions with no maintenance beyond recharging. Sealed-cells have received and are continuing to receive especially intensive development. The principal uses of these batteries are in cordless household appliances, cordless power tools, communications equipment, photographic flash lamps, emergency lighting, medical instruments, prosthetic devices, electrical instruments and artificial satellites.

C. The Case of Improved Stability of MOS Transistors and Integrated Circuits.

The computer industry, the military, and the aerospace, instrumentation, and home electronics markets have placed ever-increasing demands on the semiconductor industry for smaller size, more economical, and more reliable solid state devices. This has forced the semiconductor device manufacturers to create a new technology which has been entitled "microelectronics" and from which a new group of sophisticated devices has emerged called "integrated circuits."

Metal oxide semiconductor (MOS) devices, first introduced in the early 1960's, have the advantage over discrete conventional devices in requiring fewer processing steps, and in having smaller geometries, greater device densities and lower costs. MOS devices are a necessary prerequisite to the development of large-scale integration of complex circuits. Until recently, such devices could not be used extensively, because they were electrically unstable. The problem was eliminated by extensive research into developing a better understanding of semiconductor surface physics; the use of purer materials, cleaner processes and improvements in the chemical vapor deposition of dielectric materials; and ultimately the use of improved passivation techniques.

NASA has long been concerned with overcoming the stability problem of MOS devices to increase their long-term reliability, so as to exploit their advantages for critical space applications. NASA efforts led to an increased understanding of the semiconductor material-oxide coating interface (05-08-02); aided in identifying the failure modes in

MOS devices and LSI integrated circuits (05-08-04); brought about the development of techniques to deposit clean oxides (05-08-06); improved the reproduceability of the oxide coatings (05-08-07); developed methods to restore devices made defective by extended exposure to radiation (05-08-01); and helped several businesses in improving their products by providing them with technical assistance in meeting stringent NASA requirements (05-08-09). These contributions helped advance the technology of MOS transistors and integrated circuits more rapidly than it would have and therefore brought stable MOS devices onto the marketplace earlier than they would have otherwise.

Practical devices using stabilization techniques such as those mentioned above were not manufactured until 1968. Numerous organizations have contributed to the development of acceptable techniques, and these are now used extensively as a routine part of manufacturing process. Included are firms such as Intel, Fairchild, RCA, IBM, Texas Instruments, Motorola, General Micro Electronics, and Hughes. MOS devices are now being extensively used in military, aerospace, and industrial applications, instead of conventional discrete devices, to increase reliability, reduce size, and reduce weight. Total sales of MOS devices were $68 million in 1970 or 16 percent of the total monolithic integrated circuits market of $432 million. MOS sales are estimated to increase by 65 percent in 1971 to $102 million.

While MOS devices represent a significant market on their own, the market figures do not tell the whole story in that the modern electronics industry is almost wholly dependent on the semiconductor industry in satisfying market needs, with an increasing role being played by integrated circuits (by 1974 integrated circuit sales are estimated to exceed 50 percent of total semiconductor sales). The high-volume uses of integrated circuit devices in the decade of the 1970's will most likely be in: computer terminals, miniature calculators, mini-computers, and data transmission. It is in just such types of electronic equipment that stable MOS integrated circuit devices will be required.

NASA's space activities would be severely curtailed without access to sophisticated electronics and, in turn, integrated circuits. Size and reliability, two of the three major advantages of the integrated circuits technology, are key prerequisites to the vehicular-borne communications, guidance, data collection, and biomedical surveillance systems which NASA requires for effective aerospace research and operations. These requirements led to the advancement of MOS technology which, in turn, has contributed to the availability of stable MOS devices.

D. The Case of High-Power Microwave Transistors

Microwaves first came to widespread public notice through World War II application in radar. The frequency range of these wavelengths falls between the UHF (ultrahigh frequency) used for television, and the IF (infrared) light bands. Microwaves have characteristics similar to light in that they travel in straight lines, can be reflected, and can be focused and directed in a beam. They have advantages over and above those of light in that they generally pass through rain, smoke, fog, and nonmetallic materials such as plastics and wood. These characteristics make microwaves attractive for applications such as long-distance, line-of-sight communications and control of navigation.

Until quite recently, the most active users of microwave systems have been the military, aerospace, the telegraph and telephone industry. Increasing availability of microwave semiconductor devices, improved fabrication techniques, and, most important, declining military markets, have prompted a revolution in engineering and marketing attitudes and a marked increase in efforts to apply microwave technology to commercial and consumer needs. The major new areas now being considered and explored are:

- Industrial heating. Devices which exploit the directive properties of microwaves for selective heating are now being developed. Industrial heating sales are expected to exceed $100 million by 1975.

- Civil aviation. To overcome the air traffic control crisis, microwave systems are being planned for instrument landing systems, for en route identification, surveillance, and automated processing systems, and for visible displays of runways in zero-visibility landings.

- High-volume data, video, and voice communications. These systems will depend on millimeter-wave equipment to overcome the communications log jam that is developing. The data communications market alone, exclusive of terminals, is estimated to exceed $2 billion by 1975, with microwave relays playing the most significant part in the transmission of computer traffic.

- Laser systems. These systems can be used for high-accuracy drilling and welding of miniature parts, cutting and aligning, and can cut or drill such materials as diamond.

- Low-cost radar. Use of low-cost radar devices in applications such as police traffic control work can open whole new markets.

C.2

The growing microwave systems field appears to have been most significantly affected by advancements in the accuracy in the microwave semiconductor industry. One of the most significant developments in this field is the development of high-power, high-frequency transistors.

NASA has played a major role in the development of high-frequency power transistors. A NASA requirement for a transmitter with 20 watts output to operate in the 2 megahertz frequency range for satellite communications applications led to a NASA-funded program at RCA in 1963 to develop a high-performance, high-frequency, power transistor which would be effective in the desired frequency spectrum. From this effort RCA developed a new line of high-frequency power transistors which have wide application in the growing communications industry. In addition to establishing a new commercial product line, RCA was able to develop improved processing techniques and to generate new information about solid state materials.

The use of transistors in microwave communications had been limited because, until recently, transistors were unable to operate effectively at microwave frequencies. Now high-performance transistors, similar in concept to the NASA-RCA device, are used in microwave communications systems for all applications where amplification is required below about 1 gigahertz. The ability to provide substantial gain with relatively low-power consumption makes the microwave power transistor the most desirable amplification device for microwave repeaters and for FM terminals.

Availability of such solid state devices has resulted in the introduction of a new line of microwave equipment, superseding older, vacuum-tube versions, and providing improved performance, increased reliability, smaller size, lower costs and reduced power consumption. The single remaining tube, a travelling-wave tube, is also being threatened by solid state replacements. Once this has been achieved microwave communications systems used for long-distance telephone communications and data transmission will be entirely solid state.

Operating revenues from telephone and telegraph, radio and television, and other communications services are expected to exceed $28.0 billion in 1971. The Department of Commerce forecasts that revenues from these sources will exceed $39.0 billion in 1975 or a 40 percent increase. Revenues from international telephone and telegraph services, by far the fastest growing segment of the communications industry, are expected to total $664 billion in 1971.[1]

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1. Electronic Equipment and Components. U.S. Industrial Outlook, 1971. Washington, D. C.: U.S. Department of Commerce, Bureau of Domestic Commerce, 1971, p. 298.

V. CONCLUSIONS

The general conclusions of this study concerning NASA contributions to the advancement of major developments in selected fields of technology include the following: (1) the NASA contributions are indirect and varied; (2) the NASA contributions become "embodied" in the advanced technology of a field; (3) the major effect of the NASA contributions was to cause technological advancement to occur earlier than it would have otherwise; (4) the NASA contributions represented all levels of technology, including step-changes, incremental advances and consolidations; (5) the NASA contributions were in all stages of developmental activity; and (6) the impact of the NASA contributions ranged from low to moderate-to-high.

From these conclusions it becomes apparent that, in effect, NASA's role in advancing technology has been to create a demand for the technology to fill. Further, by creating this demand, NASA apparently aided industry, in several cases, in carrying out their own development efforts to further advance the technology in a field, resulting in new products and processes.

The impact of NASA contributions appears to be related to those factors which are inherent in the contribution as well as those factors which deal with the uses to which the contributions are put. If the NASA contribution can be thought of as a stimulus and the impact as a response, there does not appear to be too great a time lag between the stimulus provided by NASA's technological efforts which resulted in the contributions and the response in the form of technological and scientific impact brought about by these contributions. That is, most of the technological and scientific impact a contribution is going to have is felt within a reasonable time after the contribution occurs. For the identified contributions, 70 percent of the technological impact and 90 percent of the scientific impact has already been realized.

On the other hand, the rate at which the economic impact of NASA's contributions is felt, appears to be related to the rate at which the contributions find nonaerospace application. In many of the areas of NASA contributions, industry is ready to take immediate advantage of the technological and scientific stimulus provided, with a resulting economic impact. In many other areas, however, a gap apparently exists between the NASA stimulus and the ability of industry to respond. In these cases, only a small proportion of the potential economic impact inherent in the NASA contribution can occur.

The net result is that with only one-quarter of the identified NASA contributions being applied commercially, the amount of economic impact felt to date is less than one-third of its potential total impact. With a greater rate of commercialization, the economic impact of NASA contributions could be expected to rise sharply.

APPENDIX A

THE FLOW OF INFORMATION ABOUT NASA CONTRIBUTIONS

A direct communication link does not often serve to connect information about a NASA contribution and a nonaerospace user or adopter of this contribution. Instead information about the contribution is usually diffused through a network of many different channels, many different receptions and redisseminations, and among many sources and receivers.

The flow of information about NASA technological contributions to secondary users in the nonaerospace community may be part of a more complex process than the flow of information to users in the aerospace community. Except in those cases where the users of the information are members of both communities, the secondary users may be a less easily identified audience. There are numerous cases in fields such as cryogenics, high-temperature metals, integrated circuits and telemetry where close professional and commercial ties exist between the aerospace and nonaerospace communities, facilitating the flow of information about NASA contributions. In other fields, such as materials joining and machining, there may be little if any connection with the aerospace community.

A. Dissemination of Information on NASA Contributions

The major channels used for disseminating information about NASA contributions in each field of technology is given in Table 6. Each field appears to have its own "style" of dissemination, with fields such as gas dynamics and high-temperature metals making heavy use of formal non-NASA channels such as conferences, professional journal papers, and professional committee activities. In contrast, fields, such as joining and machining rely heavily on NASA channels, such as contractor reports and Tech Briefs.

For all of the NASA contributions from the twelve fields, the most frequently used channels were: NASA contractor reports (62.8 percent); technical interchange with contractors (35.8 percent); Tech Briefs (29.2 percent); conference and meeting presentations (28.1 percent); publication in professional journals (24.3 percent); personal contact during meetings, conferences and in other organized groups (24.0 percent); and NASA Special Publications (23.0 percent). This represents a well-rounded mix of formal NASA channels, formal non-NASA channels, and informal NASA and non-NASA channels.

B. Markets for Information on NASA Contributions

A profile of potential recipients of information by industry and job function was developed for each identified NASA contribution. Information for these profiles was obtained through interviews with the NASA engineer, scientist or manager directly concerned with the contribution or having the most knowledge of the contribution. In cases

TABLE 6

MAJOR CHANNELS USED FOR DISSEMINATING INFORMATION ABOUT NASA CONTRIBUTIONS IN SELECTED FIELDS OF TECHNOLOGY

	Cryogenics	Energy conversion	Ceramics	Metals	Integrated circuits	Gas dynamics	Machining	Materials joining	Microwaves	NDT	Simulation	Telemetry	12 Fields
Formal NASA report channels													
TR			X						X				
TN		X	X	X		X		X	X		X	X	X
TM	X	X		X		X	X	X	X	X	X	X	X
CR	X	X	X	X	X	X		X		X	X	X	X
SP	X	X		X		X				X	X		X
NASA TUD Program													
Tech Briefs	X	X	X	X			X	X		X		X	X
Tech Surveys											X		
Other formal NASA channels													
Request for proposal (RFP)			X	X									
NASA-sponsored conferences		X		X	X	X			X				X
Patents		X		X			X		X		X	X	X
In-house documents	X			X	X	X				X		X	X
Public relations talks		X											
Congressional testimony		X											
Awards				X									
Formal Non-NASA channels													
Conferences and meetings		X	X	X	X	X			X			X	X
Courses taught by NASA				X		X			X				
Other government reports						X							
Texts and handbooks				X		X							
Professional journals		X	X	X	X	X			X		X	X	X
Trade magazines	X	X	X	X	X	X			X	X		X	X
Committee activities				X		X						X	
Professional awards						X						X	
Informal NASA channels													
Contractor relationships	X	X	X	X	X	X	X	X	X			X	X
Technical assistance	X		X	X			X						X
Visitors and telephone calls	X		X	X		X	X					X	X
Informal non-NASA channels													
Movement of NASA personnel									X				
Personal contact		X	X	X	X	X			X		X	X	X

where information could not be obtained through NASA personnel, the profile was constructed by the project team member concerned with that field of technology. In all cases, each profile was reviewed by at least two team members.

A total of 41 different major industrial groupings were identified as potential recipients of information about the NASA contributions to the 12 fields of technology. Of the 41 industries, the ten with the greatest potential interest, in order of importance, are as follows: (1) electrical equipment; (2) transportation equipment; (3) fabricated metal products; (4) primary metals; (5) machinery; (6) instrumentation; (7) chemicals; (8) electric and gas utilities; (9) petroleum refining; and (10) air transportation.

As expected, each field of technology has its own major industrial markets for information about the NASA contributions. These major markets represent 20 different industries, and are shown by field of technology in Table 7.

The varying nature of NASA contributions and the differences between fields of technology indicates that the job functions of individuals in each field who are potential markets for information about the contributions will also vary. Overall, 80 percent of the contributions were determined to be of interest to individuals who are in product-oriented positions, such as design, development, process improvement and production; 63 percent of the contributions should be of interest to those in research-oriented positions; and 22 percent to those in management-oriented positions.

Distribution of job functions by field is shown in Table 8. Some fields are markedly different in terms of the type of person who represents a potential market for information about NASA contributions. For example, 21 percent of the NASA contributions in the field of simulation should be of interest to people in education or training-oriented positions, while only 17 percent of the contributions should be of interest to those in product-oriented positions. This is contrasted with a field such as machining, where information about all of the contributions were determined to be of interest to product-oriented people and none to education or service-oriented people.

TABLE 7

MAJOR INDUSTRIAL MARKETS FOR INFORMATION ABOUT NASA CONTRIBUTIONS IN SELECTED FIELDS OF TECHNOLOGY

Industry	Field of Technology										
	Cryogenics	Energy Conversion	Ceramics	Metals	Gas Dynamics	Integrated Circuits	Machining	Materials Joining	Microwaves	NDT	Simulation	Telemetry
Fisheries												X
Ordnance											X	
Food	X											
Chemicals	X											
Petroleum refining	X											
Ceramics			X									
Primary metals	X			X			X	X		X		
Fabricated metal products	X		X	X			X	X		X	X	
Machinery	X			X			X	X		X	X	
Electrical equipment	X	X		X		X	X	X	X	X	X	X
Transportation equipment	X	X	X	X	X		X	X		X	X	
Instrumentation	X							X	X	X	X	
Water transportation												X
Air transportation					X							X
Communication									X			X
Electric and gas utilities	X											
Medical and health services		X								X	X	
Educational services										X	X	
Non-NASA Federal agencies	X				X						X	
State government											X	

TABLE 8

JOB FUNCTIONS OF INDIVIDUALS IN SELECTED FIELDS OF TECHNOLOGY WHO ARE POTENTIAL MARKETS FOR INFORMATION ABOUT NASA CONTRIBUTIONS

Field of Technology	Job Function, Percentage*				
	Product-Oriented	Research-Oriented	Management-Oriented	Education-Oriented	Service-Oriented
Cryogenics	98	75	2	4	4
Energy conversion	48	93	--	--	--
Ceramics	50	83	25	--	4
Metals	77	56	12	--	--
Gas dynamics	100	72	76	--	--
Integrated circuits	97	23	50	--	--
Machining and forming	100	64	36	--	--
Materials joining	98	70	7	9	--
Microwave systems	100	71	35	6	--
NDT	94	19	16	10	13
Simulation	17	71	29	21	8
Telemetry	29	93	36	7	21
Twelve fields averaged	80	63	22	4	3

* Percentage can add to more than 100 in any one field of technology since markets for information about NASA contributions are not limited to individuals in any one job function.