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A Case Study in Technology Utilization

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INDUSTRIAL PRODUCTS AND PRACTICES

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A CASE STUDY IN TECHNOLOGY UTILIZATION

INDUSTRIAL PRODUCTS AND PRACTICES

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INTRODUCTION

The spectacular successes of the Apollo program have been witnessed by millions of people, as one astronaut after another has moved about and worked on the face of the moon. As the average TV viewer watches a Lunar Module rise from the moon's surface, he may marvel momentarily when the TV anchorman describes the hostility of the environment outside the spacecraft; he may be somewhat overwhelmed as he wonders about the communication systems that constantly inform the crew and ground control of the exact position and orientation of the vehicle and the status of its hundreds of life sustaining systems, the control systems that produce near perfect orbital insertion, or the propulsion systems that hurdle the lunar module into the black sky. What he may never reflect on or appreciate more than fleetingly is the extent to which these accomplishments built upon, and in turn extended, the huge base of technological competence found in American industry, a base so fundamental to our way of life.

In pursuit of such missions as Apollo, the National Aeronautics and Space Administration has called into being unique equipment that obviously has little direct application beyond the achievement of mission objectives. Yet, to assume that further direct application of space program hardware is somehow a measure of the industrial benefits accruing to the nation is to misunderstand how the creation of new technology affects modern industrial capability.

This document presents a profile of the significant ways in which technological developments in response to aerospace mission requirements have been coupled into industrial practice, with the result being that improved products and processes are now being utilized to benefit the nation. The examples used here to illustrate the different modes of technology utilization are deficient in one area: it has not been possible to capture the essential role of imaginative and dedicated people in effecting the secondary utilization of aerospace technology. It should be understood, however, these people--within NASA, the family of NASA contractors, and in the professional, technical, and industrial communities at large--provide a crucial ingredient in the different modes of technology utilization described here.

AN OVERVIEW: THE MODES FOR NEW TECHNOLOGY UTILIZATION IN INDUSTRY

While awaiting the flight of Apollo 17, visitors to Cape Kennedy were told about "a unique partnership" between government and industry that was to culminate in this last planned moon expedition. The vehicle assembly complex and the launch of the Saturn V rocket itself provided compelling testimony for the effectiveness of this partnership. The Saturn and the flight capsules alone have some eight million manufactured components, organized into thousands of interacting systems, an assembly that comments directly on the scale of NASA's involvement with American industry for the past 15 years. This involvement has left its mark on industry, particularly in the way new industrial products are manufactured. New alternatives in the design of essential machinery, instruments, and components, together with improvements in the basic processes used in manufacturing, are a direct consequence of the NASA/industry relationship.

The NASA influence on industrial products and practice stems from the inherent research and development orientation of the NASA program itself. NASA research and development (R&D) activity spans some 33 major technical disciplines that are part of the mechanical, electrical, chemical, aeronautical, materials and structural engineering fields. Further, the Agency's conduct of R&D has two essential features that maximize its effect on industrial production and practice:

- As the literally thousands of specific R&D investigations have been continued or completed, the frontiers of the various engineering fields have been extended and the resulting progress documented.

- The bulk of NASA's R&D funding has been expended in industrial organizations, where technical gains in the engineering fields occur in an environment of strong resident engineering capability and industrial capacity.

These two characteristics, preserving technical gains and a strong reliance on qualified research and development by industrial firms, form the foundation for the embodiment of new technology.

A prime reason for the dominant role of the aerospace sector in technology generation is its heavy R&D emphasis and, in particular, its willingness to undertake large-scale, high-risk research. Traditionally, business firms have not supported research programs unless they had a high probability of economic return through the sale of a product or provision of services in the marketplace. However, a federal program office may contract for research and development work with firms that have a specific research capability, but not necessarily the related production capability. Thus, it has become economically feasible for a firm to conduct certain research and development, even though it might not lead to an engineering and production contract.

As a result, the number of capable firms conducting research expanded substantially beyond the number which previously recovered research investments through production. As the size of the research effort expanded, and new organizations undertook R&D, the number of innovations multiplied. The R&D organizations which were not committed to traditional production methods often brought fresh approaches and experimentation to the areas of engineering design and manufacturing processes, thus further advancing the state-of-the-art. The very scale of this activity has set the stage for the broad advance in commercial industrial practice that is now underway.

How has aerospace technology transferred and diffused to other economic sectors to permit secondary utilization of the technology? There are many modes, or forms of transfer/diffusion, which interact in a very complex way to enhance the movement of technology among sectors. Several of these modes have been identified. They include:

- Diversification by firms producing for the aerospace sector that: (1) shift production facilities and personnel from aerospace to commercial products, or (2) implement formal organizational policies that bring continued application of their aerospace experience in commercial markets.

- The general improvement of industrial production practice and product quality through NASA-initiated specifications and standards for space program hardware procurement.

- Development of new process and product technology by industrial contractors to promote the direct interests of aerospace programs, with subsequent commercial production occurring because other markets and applications are recognized.

- Intersectoral diffusion of technology generated through long-term basic and applied research and development in materials, apparatus, and processes by the dissemination of results through professional societies, industrial design codes and published documentation.

- Relocation of skilled individuals from aerospace employment to employment in a different economic sector, resulting in adoption of aerospace technology to solve analogous problems encountered in the new sector.

- Public-interest transfer of space program experience to nonaerospace organizations through a planned program linking the NASA/aerospace sector with commercial firms and public sector entities.

In the descriptions that follow, several examples are presented to illustrate each of these modes. Taken together, it will be seen that NASA R&D activity has had a pervasive impact on American industry, and the momentum is building.

MODE I: Diversification by firms producing for the aerospace sector that: (1) shift production facilities and personnel from aerospace to commercial products, or (2) implement formal organizational policies that bring continued application of their aerospace experience in commercial markets.

Since 1961, when President Kennedy summoned the United States to achieve the status of a spacefaring nation second to none, NASA's policy has been to rely upon contracts with many nongovernmental establishments to help accomplish its various missions. Over 90 percent of all funds invested in NASA programs have been spent outside the government; in some years, this has reached 95 percent. These programs have involved about 20,000 industrial prime and subcontractors and suppliers, 200 universities, and during the peak year of 1965, over 400,000 government and industry workers (Webb, 1968).

These contracting organizations and the people they employ contribute existing research capabilities, manufacturing facilities, and production expertise that government facilities do not have. Likewise, they invariably acquire a residual capability from their NASA experience that in many ways is valuable to commercial and industrial enterprises. This residual capability is shaped by the subtle nature of the technological contributions associated with space research--new techniques in metal fabrication, new materials, improved engineering analysis techniques, vastly improved reliability and unparalleled safety. Sometimes the commercial products marketed by NASA contractors are the direct descendants of aerospace products; but much more often, such products embody the new knowledge gained when a company does R&D for NASA.

While this technological subtlety makes it difficult for the "man-on-the-street" to identify benefits of aerospace research, many industrial firms are capitalizing on their NASA experience. The following examples illustrate how only three companies--North American Rockwell, Bendix, and TRW--have implemented programs to further utilize capabilities that have been created or expanded because of their aerospace contracts.

North American Rockwell Corporation (NAR). North American has been one of the major NASA contractors throughout the space program, having designed and built the Apollo capsule, the S-II stage of the Saturn, all of the Saturn engines, and numerous other hardware systems. Prior to a 1967 merger, North American Aviation was an aerospace firm with 97 percent of its business coming from the government; Rockwell-Standard was an industrial firm with strengths in commercial production and marketing know-how, but short on technology. Among the stated intents of that merger were (Meechan, 1969):

> North American was seeking to broaden and stabilize its business base via a major commercial outlet.
>
> Rockwell was interested in availing itself of sophisticated aerospace technology to improve and expand its product lines and processes.

In 1971 NAR underwent a major organizational realignment designed to focus its strength on four main marketing areas: aerospace, automotive, electronics and industrial products. The company also formalized its internal technology transfer program at the corporate level, headed by the vice president of research and engineering. Most, if not all, NAR technology transfer projects can be put into one of three "intent" categories, namely: to enter the marketplace with a new product; to expand current markets with improvements to existing products; or to reduce production costs with new or improved processes.

The North American Rockwell Microelectronics Company (NRMEC) TA-4 calculator is an example of the first intent--creating new products. NAR is one of the world's leading designers and producers of microelectronic systems based on so-called MOS/LSI (metal oxide semiconductor/large-scale integrated) circuits, and company engineers have pioneered in aerospace electronics development for NASA for more than a decade. This expertise was recently directed to the development of a "consumer calculator" that can be used for a number of household problems and sells for under $100. Over 200,000 of these all-purpose, super-fast machines have been sold to mass merchandisers such as Lloyd's Electronics and Sears Roebuck and such large mail order distributors as Logic Data. NRMEC officials project sales of nearly one million units over the next three years (Skyline, 1972).

Examples of the second intent abound--an electronic printing press, a computer-assisted brake control system for trucks, a digital-controlled phototypesetter, paper cutter controls, and an electronic knitting machine are just a few. This latter machine can illustrate the impact of NAR's directive to capitalize on its aerospace experience. The ElectroKnit-48 was a joint development between the Electronics Group and NAR's Textile Machinery Division. It involved a unique marriage of electronics and electro-systems technology to a previously all-mechanical system. The result has been a new standard of excellence in knitting machines. While the ElectroKnit-48, which is controlled by magnetic tape, costs more than mechanical units--$56,000 compared with less than $50,000--it produces one-third more fabric with the same number of operators. Moreover, the ElectroKnit-48 pattern can be changed in hours instead of the days that it takes with a mechanical unit--a key competitive factor in the volatile world of fashion. Marketing director Walter H. Imboden has stated that seven of the ElectroKnit-48 units are working in U.S. mills and 125 more will be shipped by year-end, including 20 to Italian mills. Still, this only scratches the surface; in the U.S. alone, 16,000 to 18,000 double-knit machines are producing 500 million pounds of fabric a year. Yet, even such a competitor as the Singer Company calls the ElectroKnit machine "the wave of the future" (Business Week, September 9, 1972).

In response to the third intent of the NAR technology transfer program, the main focus is on using people as transfer agents. For example, a group of engineers from the Space Division conducted an extensive stress analysis on an automotive brake drum which is being designed and fabricated by the Automotive Group of NAR. In such cases the interaction may be short term or, eventually, lead to a permanent assignment of aerospace engineers in the commercial division (Goldstone, 1972).

Bendix Corporation. The primary goal of the technology transfer program at Bendix is to turn aerospace research and development capabilities into an average of one, viable new business a year. To help accomplish this, Bendix established its Advanced Products Division (APD) in June 1969. The technology transfer program at Bendix builds on years of experience in aerospace hardware development, including multispectral scanners, pattern recognition equipment, photointerpreters, and a host of control systems for the Saturn/Apollo vehicle and ground support facilities. The introduction of three new programs over the past three years has demonstrated APD's ability to meet the goal established by the company.

The first project to be launched, which coincided with the formation of Bendix's formal technology transfer organization, was in computer graphics. Specifically, Bendix selected the area of man-computer interface equipment, an area they believed would have a growth rate even higher than that for computers. It includes various types of electronic digitizers, plotters, computer output microfilm, automated design systems and related software. The target market segments for this line of products include engineering and scientific graphic digitizing, automated design, numerical control tape preparation, automated manufacturing and inspection, photogrammetry and earth resources mapping applications, and general purpose graphic input terminals for various types of computers.

The second technological concept that Bendix launched as a commercial venture was pattern recognition. The company, as part of its aerospace research and development, had achieved a leading capability in applying this technology to the processing of pictorial patterns from aerial photographs, as well as nonpictorial patterns such as those from sonar signals and automotive diagnostic signals. The particular technical areas Bendix is interested in include laser optics, acoustic holography, and computerized control and information processing. Bendix foresees viable commercial markets for the technology in optical defect recognition and fault diagnosis for both aircraft and automobiles.

Pattern recognition technology also shows high potential for further automation of manufacturing, warehousing, and other activities involving sorting systems. For example, Bendix developed a label reader which has been added to its basic line of recognition systems. Recently, it received a $200,000 order for label readers to be used in an automated warehouse. The unit will be able to read digital labels at any angle and is compatible with all digital computers.

The company sees a major growth market in equipment and techniques dealing with the interface of "the analog world with digital computers," according to C. B. Sung, vice president and group executive of Bendix's Advanced Technology Group which is responsible for the Advanced Products Division. In line with this philosophy, the company's third technology transfer venture was launched through the acquisition of a small Boston-based company that had developed a concept for a portable computer terminal. Bendix transferred the company to Southfield, Michigan and renamed it the Bendix Interactive Terminals Corporation. Its original product line was expanded, and the company is now bringing out a second generation of portable computer terminals. Entering its second year, the new company is either on or ahead of schedule in meeting APD profile milestones, according to Vance R. Kloster, general manager of the Advanced Products Division (Yaffee, February 14, 1972).

At Bendix the transfer of management personnel is, in many cases, as important as the transfer of technology or a product itself. In each of the above examples the aerospace program manager serves as the chairman of the new business planning team, which includes specialists in marketing, research, finance, planning, law, production and commercial development.

In other cases the technology or technical capability is the primary focus. For example, Bendix's hybrid computer simulation of complex control systems developed originally for NASA's AAP and Skylab Programs was instrumental in the development of electronic fuel injection for automotive engines (Blumenthal, 1972). Electronic fuel injection eliminates the carburetor, cuts harmful emissions and increases engine efficiency. A simple, computer-like controller monitors combustion temperature and pressure, engine speed, and air flow, then prescribes a precise amount of fuel for each cylinder. The 1972 Volkswagen sedan and squareback models already have electronic fuel injection systems developed by Bendix, and company officials feel that U.S. auto makers will install these systems on their 1974 cars (Business Week, December 9, 1972).

TRW, Incorporated. The complexity, size, and urgency of the ballistic missile effort forced the ordered application of what is most often called systems engineering. Systems engineering--and many of the people practicing it--was substantially advanced by manned and unmanned spacecraft projects. Rather than a single discipline, systems engineering is actually the synergistic combination of many disciplines. More than that, it is a state of mind or a thought process which causes people to view a complex problem as a series of smaller, solvable problems, each interconnected and interrelated so that the solution of one impacts on the solution of another.

Some of the same people at TRW who applied the systems approach to aerospace and defense problems are now helping to solve problems of a different nature--electric power networks, production processes, land use planning and transportation. Since 1970, 25 computer experts from TRW Systems have been under subcontract to TRW Controls, a major producer of automatic computer controls, to develop real-time programs for electric power dispatch computers. One specialized program, the TRW Executive program, was adapted from the Apollo Guidance Computer System and is now standard in the company's larger monitoring and control systems. The first of these systems was installed for the General Public Utilities Corporation, which serves 1,300,000 residential, commercial, and industrial customers in a 25,000-square mile area in Pennsylvania and New Jersey. Three more of the systems have been installed or are on order, including one for the Bonneville Power Administration to control the Federal Columbia River Power System.

Another way that TRW has been able to capitalize on its NASA experience is by improving industrial production processes. For instance, the production of turbine blades for large aircraft engines had been considered a black magic art. In spite of large-scale production runs, the blades still required many hand operations. By adapting both the sensing techniques developed for satellites and instrumentation for measuring precise contours, turbine blade production at TRW is now more automated. In fact, blades are now produced and shipped in broad functional categroies instead of the former noninterchangeable engine sets.

In another industrial example, the quality control of automotive steering pumps was substantially improved when space age technology was used to design an end-of-the-line analog computer that simulated the actual steering pump environment. When properly programmed, the computer "told" the final inspector exactly how the pump would perform when installed on an automobile in a fraction of the time previously expended (Lundy, 1972).

The Ontario Province in Canada is concerned that the natural migration of people and industry into the region between Toronto and Detroit be orderly and well-planned. With the help of TRW Systems technology, it is planning its future and setting goals for the kind of urban and suburban areas it wants. A 3,000-acre "land bank" has been designated as the site for a model rural city. TRW is performing an objective analysis of the resources, needs, and potentials of the area and will propose recommendations to support total development for the region (Rosen, 1972).

The applicability of systems technology to transportation problems is illustrated in TRW's study of the high-speed ground transportation system between Washington and Boston. Not only does this study provide answers about the rapid flow of people and products over this corridor, but it also serves as a model for other high density transportation corridors throughout the world. TRW System's technology has also been directed to the problem of access to airports. In studying Kennedy International, all arteries--roadway and railroad--were considered as potential candidates for moving people, baggage, and products between the airport and surrounding communities. Kennedy posed a unique problem in that the air terminal was already established and facing an uncontrollable expansion problem. TRW recommended the access system that offered the best performance and the most benefits.

In some of these cases, the importance of systems engineering has been proven; in others, time will better judge the value of the systems approach. Yet, in all cases, methods of analysis which were unavailable only a few short years ago have been called upon to assist in the solution of extremely difficult problems.

Perspective. There can be little doubt that aerospace contractors are capitalizing on their NASA experience; the myriad of examples in this section have supported this belief. It seems reasonable, however, to question whether or not these examples represent "accidents of transfer" or if they are well-founded and can expect to continue, perhaps even on a larger scale. An absolute answer, of course, can only be provided in time. The underpinning rationale for the contractor activities illustrated in this section is that various product lines within a firm rely upon a common technological base. Thus, when a venturesome program such as the space program calls into being expanded technical capabilities, other product lines sharing the technology also advance. The ultimate beneficiary is the consumer, whether he is another industrial firm or a private individual.

MODE II: The general improvement of industrial production practice and product quality through NASA-initiated specifications and standards for space program hardware procurement.

In space you don't often get a second chance! This fact has led to NASA's insistence on the highest reliability and quality assurance for space program hardware. Every assembly, component, and part must be proven reliable; no margin of error can be permitted where lives can be endangered or where the failure of a single part can easily abort an entire mission worth millions of dollars in equipment and preparation. Manned spaceflight created new and more exact quality assurance methods, initiated new procedures to identify potential trouble spots, and improved manufacturing processes that culminate in near flawless products. The manufacturing sector has capitalized on these gains by applying them in nonaerospace production activity.

Several developments in reliability and quality assurance are presented to illustrate some of the ways that production practices have been improved through industry's participation in aerospace manufacture.

Certified production line. In 1964 NASA initiated its microelectronics reliability program to promote solutions to a variety of problems inherent in miniaturizing electronic systems. A NASA steering committee established procurement standards for microelectronic products and conceived a reliability program to assure that manufacturing practice was the best available.

This program was based on a concept novel to the space program--the concept of product line certification. NASA concluded that it was unnecessary and too restrictive to direct contractors in how to design manufacturing processes and build circuits, as well as to perform qualification tests on every portion of their manufacturing line. Instead, NASA required that the contractor establish methods assuring proper control and evaluation of its manufacturing processes. A NASA team then inspects the contractor's manufacturing line and, if satisfied that the contractor's control/evaluation systems are adequate, the team certifies the line for the the NASA procurement. During site visits leading to certification, the NASA team reviews the manufacturer's production methods, procurement specifications, vendor grading system and receiving inspection procedure. Also during such visits, the NASA team often helps improve the manufacturer's processes and controls by providing advice on nonproprietary methods used elsewhere, based on broad experience with many processes and types of equipment derived from hundreds of similar inspections.

To help contractors implement the product line certification concept, NASA established environmental and functional test methods for microcircuits. The Department of Defense later adopted the concept and worked with NASA to develop a series of joint standards which apply to contractors manufacturing microelectronic systems for space and defense use.

NASA could have chosen to specify that contractors establish a special, high reliability production line for the manufacture of space program microelectronics. The "captive line" approach might have provided acceptable products more quickly by permitting concentration of premium production facilities, but it also would have significantly increased NASA's costs because of the generally low production volume of NASA procurements. Instead, the Agency encouraged implementation of high reliability processes on the contractors' standard production lines. By doing so, the spillover of microelectronic technology to commercial products has been dramatically stimulated. Even where a production line may be producing television components, and strict NASA reliability standards are not essential, the tighter quality controls provide a higher yield of acceptable microcircuits. In an industry where a yield increase of one or two percent is extremely valuable, one manufacturer obtained a 20 percent yield improvement after certification (Hamiter, 1972).

A scientist at NASA's Marshall Space Flight Center pointed out several reasons for the success of the microelectronic reliability program in stimulating contractor innovation. Dr. A. M. Holladay stated NASA's purpose to be "to assure that the manufacturing process is under control, but not to tell the manufacturer how to produce nor which process to use." He added that companies are urged to introduce new methods if they are better and are under control. In this way, the certification program does not stifle innovation (Holladay, 1972).

Scanning Electron Microscope (SEM). During research on miniaturization of electronic circuits, scientists at the Marshall

Space Flight Center searched for some way to obtain visual inspection of the extremely tiny microcircuit components. Submicroscopic defects caused by chemical impurities or mechanical strain were suspected to cause microcircuit failure, yet the inability to observe such defects made corrective action difficult.

To solve this problem, NASA procured a scanning electron microscope (SEM). This device, which was only the second unit ever built, provided clear , detailed photographs with magnifications up to 5,000 times actual size. The perspective provided by the extreme depth of field makes the SEM uniquely valuable for inspecting microcircuits. The instrument has an ability to look below-surface for defects at the active junctions. The SEM also can be used to analyze chemical elements, a function analogous to that of a mass spectrometer.

NASA has used the SEM to identify structural and metallurgical causes of failure in microcircuit components. The results of SEM examination are passed along to manufacturers in the form of failure analysis reports illustrating causes of failure and indicating the production steps at fault. The use of the SEM by NASA has had two significant effects on industrial practices: it has encouraged manufacturers to improve their manufacturing processes, and it has stimulated the widespread use of scanning electron microscopes by microcircuit manufacturers. Over 400 SEM's were in use in the United States by 1971 (Holladay, 1972).

Among the microcircuit manufacturing process improvements stemming from SEM research by NASA are the use of passivated layers to insulate conductive strips, the use of noble metals and gold beam leads to reduce electromechanical fatigue failures, and the requirement for temperature-cycling stress tests to rigorously check completed circuits. The results of such improvements have included a valuable increase in production yield and longer expected service life of commercial electronic products.

Texas Instruments (TI), a major semiconductor manufacturer, has a certified production line and three SEM's. From TI's perspective, production line certification by NASA is valuable because an independent evaluation of their production methods contributes in many ways to a general upgrading of practice. Operation of the certified line serves further to enhance attention to detail and discipline. All integrated circuit production benefits from the certified line in that the front-end work for all integrated circuits is accomplished according to NASA standards. Assembly operations are separate for NASA productions, but the front-end improvements carry through to all of the lines. In addition, some learning carries over into many other areas; for example, gains in knowledge of field effects that occur on the NASA line would be transferred to any other line where the information is pertinent.

TI's scanning electron microscopes are used for quality assurance, failure analysis and research. Two are employed for in-process inspections and routine monitoring of front-end work. Process control and lot acceptance inspections require the use of an SEM, and TI hopes to expand their routine use into the assembly step. The primary values of the SEM are that it permits inspection techniques that are not otherwise possible, and it saves time. Using an SEM for failure analysis of an MOS device reduces analysis time by about half, as compared with probing methods previously used (Adams, 1972).

Failure analysis/Alerts/GIDEP. Beyond the requirement that faulty parts be eliminated from its equipment, NASA operates under the philosophy that a failed part must be considered extremely valuable because it represents an opportunity to perform a thorough analysis of the causes of its failure. The learning that follows from a failure analysis often induces significant advances in both design and manufacturing. One primary goal of failure analysis is to identify the causes of failure in a way that permits corrective action.

Step-by-step procedures move the failure analyst to finer levels of discrimination, from general screening tests to dissection to spectrographic analysis of materials used in an item. For example, a failure analysis of a shorted capacitor would begin with visual examination for external damage and proceed to radiographic inspection. Electrical measurements (e.g., capacitance, dissipation factor, dc leakage, and insulation resistance) would provide clues to the cause of the problem; and, perhaps, baking, temperature cycling, or vibration tests would be undertaken to confirm the evidence. The unit's encapsulant might then be removed, with strict care to avoid new damage that could prevent conclusive findings concerning its original failure. Dissection by grinding in small increments might reveal the failure mechanism, or it could be necessary to perform spectrographic materials analysis to discover foreign material. Knowledge of manufacturing processes for an item is essential for the analyst because the critical manufacturing steps may have been inadequately controlled.

One aspect of NASA's failure analysis activities is their scope and depth. While many manufacturers perform failure analysis, few are in a position or have the incentive to evaluate thousands of materials and components thoroughly. The sheer scale of NASA's operation and the absolute necessity of maximum reliability provided the environment and motivation to perfect techniques of failure analysis and to apply them universally. In addition, while a single manufacturer may have great expertise in a specific kind of failure analysis, he has no compelling reason to share that knowledge with others. NASA, on the other hand, has published a compendium of comprehensive failure analysis procedures and recommendations for use in industry (Lockheed Missiles & Space Company, NASA CR-114391, 1972).

Although part failures are relatively rare occurrences, a failure analysis that discloses a faulty manufacturing process or design specification implicates a whole production run or even an entire product line. Because of the possibility that similar units may fail, if one fails, NASA implemented a warning system in 1964 to inform all NASA stations and contractors of the existence and nature of component defects. Called the Alert Reporting System, it obligates all NASA installations to report "failure, malfunction, or unexpected deterioration (degradation or contamination)" of any part or material "during any phase of its life cycle." Such reports are then widely disseminated to contractors in order to avoid or minimize the recurrence of the problems and to generally improve equipment reliability.

Reception of an Alert obligates procurement officers, design engineering officals, project managers, and reliability, safety, and quality assurance directors, as well as other appropriate officials, to determine the applicability of the Alert to their areas of responsibility and to prevent further use of a suspect item until the problem is corrected. Appropriate corrective action may lead to subsequent amendment of the Alert to indicate the conditions under which the item may again be acceptable for use. Examples of the kinds of impact that follow from failure analysis and the issuance of an Alert will help clarify the manner in which these activities contribute to advancing industrial competence and product reliability.

In 1969, a major semiconductor manufacturer was notified that an Alert was forthcoming and certain faulty semiconductors were being returned. Failure analysis had disclosed the presence of nickel particles inside the protective metal case. Following issuance of the Alert, the semiconductor manufacturer conducted a worldwide search for a manufacturer who would cooperate in devising better case manufacturing methods. In addition, the firm further improved its own case preparation procedures by implementing an automated chemical, mechanical, and solvent rinse cleaning process. Beyond these measures, the company added another process step into its semiconductor production: passivation of the entire die surface. This process yields a minute glass-like coating over the surface to insulate effectively the conductive elements from any contamination inside the case. The added steps of depositing the coating and opening holes for external leads were expensive, possibly increasing production costs by eight to forty percent, depending on the item. Nonetheless, the gain in reliability was deemed more important that the cost increment, and the passivation process was implemented for most of the firm's output of several million items per day for commercial as well as government markets.

An additional positive value for the semiconductor firm, as observed by the quality and reliability assurance manager, was that his management became more sensitive to the need for in-house reliability testing. In the semiconductor industry firms tend to rely on customer feedback to identify reliability problems, if only because of the impossibility of obtaining exhaustive in-house reliability data for all units under all combinations of use conditions. Even 100 percent in-circuit testing is only a simulation of actual operation by customers, each of whom probably use a given component in a relatively unique environment. The Alert System demonstrated that thorough and competent failure analysis, conducted in-house, could increase product reliability independent of the consumer application (Straley, 1972).

Another company, Triad, Incorporated, introduced a new line of miniature transformers in 1963. Some of the transformers were manufactured for the space program, the rest for a major, original equipment manufacturer. While in-house design evaluations had indicated the possibility of trouble with the direct connection of a fine winding wire (#50) to a heavy external lead wire, the equipment manufacturer was reluctant to consider any design changes without some firm evidence of actual failure. When some of the early production units reached the Jet Propulsion Laboratory, thermal cycling was found to cause the fine wire to separate at the external lead connection. Alert R-2-65 was issued, resulting in an immediate scrapping of all units produced before January 1964. Triad then incorporated an intermediate gauge wire lead in all of its miniature transformer product lines (Wexler, 1972).

In order to extend the circulation of information regarding causes of product failures so that industrial practice generally might be upgraded, NASA, in 1968, joined with other government agencies and contractors to establish the Government-Industry Data Exchange Program (GIDEP). GIDEP now includes as participants the three military services, NASA, the Canadian Military Electronics Standards Agency, and more than 300 other government agencies, contractors, and instrument manufacturers, all of whom generate and use GIDEP technical documentation.

The primary objective of GIDEP is to minimize costs while improving reliability, particularly in matters involving testing and reliability verification where duplicated efforts escalate costs needlessly. To help in meeting this objective, GIDEP adopted the NASA Alert System as one means for keeping members informed about critical quality problems. GIDEP's function, however, is broader than that of the Alert System. Alerts are primarily concerned with removing and preventing problems relating to faulty parts and materials, while GIDEP's information base also covers parts, materials, manufacturing processes, calibration procedures and technical test data. In addition GIDEP makes available a variety of general technical reports in these areas. More than 35,000 technical reports and 15,000 calibration procedures are in the system, and more than 4,000 are added each year. Since 1960, this system has provided savings of more than $30 million to its participants.

GIDEP's Test Equipment Calibration Procedures Interchange Program has upgraded the general level of equipment calibration methods and is becoming a source of standardization of these procedures. Hewlett-Packard routinely uses the program to formulate the calibration procedures sent out with its instruments. In addition, the company recently derived a significant benefit from the program when the U.S. Marine Corps requested bids for preparing a set of computer programs for automated instrument calibration. Some

80 instruments were involved, many not made by Hewlett-Packard, and the calibrations had to conform to military standards and procedures. Hewlett-Packard had the required information instantly at hand in its GIDEP file and was able to submit a winning bid. If the company had not had the procedures in its files it could have taken easily two months to locate them, and it would then have been too late to even submit a bid (Littlefield, 1972).

NASA soldering standards. During the early years of the space program, NASA recognized that reliability of spacecraft and related electronic equipment was heavily dependent on the skill of persons soldering electrical connections. Each of the many electrical connections in spacecraft must withstand rigorous environmental and vibration conditions, yet must provide flawless electrical continuity for indefinite periods. While some early failures were traced to faulty soldering techniques, weight considerations as well as reliability were affected because of the vast quantity of electrical connections. It has been estimated that an additional drop of solder on each electrical connection would have increased the Saturn/Apollo weight above the critical level for achieving mission objectives (Perry, 1972).

In 1962, NASA's Marshall Space Flight Center began a program to improve soldering workmanship standards among space program contractors. Detailed written instructions were prepared for contractor use and issued as Procedure 158, Procedure for Soldering of Electrical Connections (High Reliability). Also, NASA established schools for training personnel in soldering techniques, first at Kennedy Space Center and later at four other centers. The Kennedy school trained NASA soldering inspectors and also trained contractor personnel as instructors, who in turn trained contractor employees in soldering techniques. Using its standards of soldering, NASA would inspect and certify the quality of the contractor's training program and would conduct certification tests for persons successfully completing a training program. The soldering schools were quite popular and successful because NASA contractors found that soldering training dramatically improved the reliability and acceptance rate of all their manufactured equipment. Labor unions in the Cape Kennedy area asked NASA to oversee their soldering schools to help their members qualify for jobs in the space program. Altogether, it is estimated that nearly 7,000 persons were trained in these soldering schools, and an additional 50,000 persons were trained by instructors who graduated from NASA schools. Today, the soldering school at NASA's Ames Research Center trains young persons enrolled in the Neighborhood Youth Corps to learn an employable skill. Although other NASA soldering schools have been closed, contractor schools continue to operate to train solderers in NASA-specified methods.

The NASA impact on the soldering practices of U.S. industry has been immense. Almost every company engaged in electronics manufacture uses NASA-developed training instructions and NASA visual inspection standards. In 1964, a NASA-wide standard for soldering was issued as NPC-200-4, Quality Requirements for Hand Soldering of Electrical Connections. The NASA standards were adopted by military services (e.g., Air Force Training Command soldering manual), and the text and illustrations from NPC-200-4 were taken verbatim and incorporated in the commercial standards of manufacturers (e.g., Hewlett-Packard's Manufacturing Engineering Manual, September 1971). The current NASA soldering instructions, NHB 5300.4(3A)-Requirements for Soldered Electrical Connections, were issued in 1968.

Recognizing the value of its soldering expertise, NASA issued a Special Publication in 1967, entitled Soldering Electrical Connections (SP-5002), that has become a widely used handbook. Also, NASA has provided a series of conferences for industrial arts educators on trade skills needed in the aerospace/electronics industry.

Quality assurance policy guidelines. During the 1950's, the complexity of military weapons systems increased rapidly, and there was a corresponding need for more sophisticated quality assurance guidelines. Several military quality assurance specifications, such as MILQ 9858 and MILQ 21549, were issued in that decade to define hardware-oriented quality assurance programs for military contractors. When NASA was formed in 1958, it became clear that more general quality assurance specifications were needed. The basic NASA quality assurance publication, NPC 200-2, defining specifications for contractors, was written in 1961 and published in 1962. The draft for NPC 200-2 was reviewed by a joint committee of NASA and Defense Department experts. Subsequently, a correspondingly general military specification, MILQ 9859A, was published in 1963. These two publications, NPC 200-2 and MILQ 9858A, were the first generic, rather than specific, quality control program definitions. The NASA document established a policy for quality control which includes the requirements for an acceptable contractor-written quality control plan and documentation (Weiss, 1972). The plan presents the specifics of compliance, such as inspection procedures and applications, scheduling on a systems matrix, and management of the quality program. The documentation includes a broad range of results, such as weld X-rays, receiving inspection reports, and management reviews.

In recent years, the design sophistication of nuclear reactor electric power generating plants has rapidly evolved from 100-megawatt units to the 1,000-megawatt units now in the construction stage. The AEC has published quality assurance licensing requirements to ensure safety of the increasingly complex nuclear plants. Prior to 1970 the AEC requirement, 10-CFR-50, resembled the specialized MILQ 9858; however, in July of that year, a major appendix was published. This appendix provides a quality control definition based on the generic approach. It also requires the electric utility to document the implementation of the program, as does NPC 200-2 (Haywood, 1972). The General Electric Company, for example, has converted its experience in implementing NPC 200-2 at Cape Kennedy under a NASA service contract for the Apollo program to a new quality assurance consulting service for the nuclear power industry. Several utilities, such as the Tennessee Valley Authority, Commonwealth Edison, and the Florida Power Corporation, are using the GE service to audit the implementation of AEC requirements. A spokesman for GE stated that the company's experience in managing quality programs under NPC 200-2 is directly applicable to managing similar programs under the AEC specifications (Warwick, 1972).

Perspective. Mode II has offered yet another perspective on the strong interaction that developed between NASA and its contractors. This section has focused on the residual capabilities created within contractor organizations as a result of NASA's unique reliability and quality assurance (R&QA) requirements. So important was R&QA to NASA, that formalized procedures affecting every aspect of product development were instituted to minimize the chance of failure. And everyone associated with the space program acquired a new sense of perfection, a capability that is being used in many ways to improve nonaerospace products.

MODE III: Development of new process and product technology by industrial contractors to promote the direct interests of aerospace programs, with subsequent commercial production occurring because other markets and applications are recognized.

Sustained research programs, such as for quiet aircraft engines, gas turbine improvements, and new and better power cycles, also yield improvements that affect the manufacturing sector. Some results of these sustained programs have already passed into the definitions of industrial best practice, such as acoustic nacelles for large aircraft. This is a direct outcome of NASA research into the mechanisms of noise generation, which found that the dominant noise source during landing approach is the fan and compressor blades. Appropriate insulation of the inlet structures was found to reduce noise significantly under approach conditions (DOT-NASA, 1971). This treatment makes the DC-10 one of the quietest jet aircraft in service, despite its large size.

Many research efforts result in advances that are directly utilized in the space program--advances that also build a foundation for commercial products and practices. This situation is exemplified in the following examples.

Underwater location beacon. An underwater search and locator system, known as the pinger, consists of a small, impact resistant unit which activates upon immersion in water and begins emitting a periodic sonar pulse. A missile, submarine, mine, or any other object to which a pinger has been attached is rather easily tracked and located with an underwater listening device.

The first pinger was developed during the late 1950's at the Naval Mine Engineering Facility, where the Mine Locator System MK1 Model 0 was built. By 1961, personnel at NASA's Langley Research Center had become acquainted with the Naval system while working on new concepts in nose cone recovery systems. Liaison between the two agencies was effected, and the pinger was successfully tested for nose cone recovery. In 1962 design changes were drawn up to reflect NASA specifications dealing with acceleration, vibration, shock, temperature and pressure environments. Then, in 1963, Langley was ready to award a contract to produce pingers for NASA use. The Dukane Corporation won the contract, while Burnett Electronics Laboratory was contracted to build a receiver. Dukane later developed a receiver with company funds, and Burnett similarly funded the development of its own pinger. Both companies now make several models of the pinger as well as the receiving equipment. Dukane's pinger received a 1967 award from Industrial Research magazine as one of the 100 most significant new products of the year. Through the years, both the range, selectivity, operating depth, and construction have been improved through research and specification efforts conducted at Langley.

As early as 1963, the Federal Aviation Administration (FAA) was seeking a means of locating aircraft flight recorders after a crash at sea and made inquiries at Langley. Successful improvements in the production of the pinger eventually led to a 1971 FAA order that pingers be attached to flight recorders of certain aircraft by March 1974. Commercial airlines are now installing pingers on a scheduled basis, and all NASA and FAA aircraft now carry pingers. The U.S. Navy, which has saved more than $1,500,000 by recovering lost test torpedos equipped with pingers, has commissioned the development of a special configuration for use on submarines. Other uses include offshore oil exploration activities, oceanographic research, deep sea salvage operations, and the Concorde SST (Lyon, 1972).

To capitalize on the capabilities acquired during development of the pinger, Dukane assigned staff engineers who were involved in the development of the pinger to its Ultrasonics Division, where they have now developed a commercial line of power ultrasonics equipment and leak detectors. Gas leaks, hydraulic bypass, and bearing wear can be detected with these new products (Lyon, 1972). Similarly, Burnett adapted its receiver for use as a leak detector. Here, the configuration of the leak detector is smaller than the NASA receiver and does not incorporate the impact resistant features; however, the same internal circuitry is used (Burnett, 1972).

Corrosion resistant paint. A more mundane, but costly, problem confronted NASA at Kennedy Space Center because this east coast region has one of the most corrosive environments in the United States. There is a constant maintenance problem on buildings and equipment and a continual threat of corrosion failure of the numerous high pressure lines which form a network through Kennedy. There has been substantial corrosion of the stainless steel pipes and fittings of the high pressure lines, as well as numerous failures of the stainless steel bellows used in insulation jackets for cryogenic lines.

To combat this ever-present corrosion threat, Kennedy's Materials Testing Branch conducted an extensive paint research program that has broadly influenced corrosion protection practices. In 1960 the Materials Testing Branch began investigating the potential of zinc-rich paints. After initial testing proved promising, the paint industry responded to NASA's requests by producing various zinc-rich paints.

About 1970, the Materials Testing Branch announced in Commerce Business Daily that it would test all types and brands of zinc-rich paint for corrosion resistance and publish the results. Accordingly, an extensive test program was initiated and has been continued, with results being published in NASA Technical Notes and in such scientific publications as the Metals Handbook of the American Society of Metals. All test results are also disseminated to industry and government through the GIDEP system. In addition, the Materials Testing Branch has published a specification, KSC SPEC F-0020, for zinc-rich coatings based on test experience and a qualified products list to help users locate sources of acceptable coatings. The Florida State Road Department is one agency which has solicited Kennedy's advice on zinc-rich coatings.

During the Kennedy research program, the Materials Testing Branch developed a concept for a new corrosion resistant coating--a nitrile rubber spray coating filled with aluminum powder. The B. F. Goodrich Company formulated a test material, known as 0-139-AR-7, based on this concept. Although Goodrich is still conducting further development tests, the company is currently marketing the AR-7 material under the name "Aerocoat AR-7." It is being used in high corrosion environments for prototype applications on offshore oil rigs, highway guard rails, and automobiles as an undercoating (Dixon, 1972).

Pavement grooving. A process development having great significance in terms of reduced property damage and personal safety is pavement grooving. Beginning in 1954, NASA launched a continuing series of studies on the phenomenon of tire hydroplaning on wet surfaces. At various times the cooperation of the British government and the FAA added new dimensions to the research, so that by 1968

NASA's initial basic documentation evolved to a comprehensive understanding of the problem and its solutions. The most promising application is to cut grooves in highways and runways, allowing water to run off the surface and increased tire traction. Optimum configurations for the grooves have been determined in experiments at NASA's Langley Research Center for a variety of possible conditions, with emphasis on runway applications.

The first experimental grooving on highways was initiated by the California Highway Department in 1961. Con-Cut, Incorporated built the original grooving equipment for this experiment and, subsequently, built upon the experience to become a major manufacturer of this kind of equipment. Continuous study and refinement and successful experience in accident reduction on highways that have been grooved since 1961 have led to an appropriation level of nearly $4 million for this year's highway grooving activities in the state (Farnsworth, 1972).

More than 20 states have grooved troublesome stretches of highway, and more than 15 major U.S. civil airports now have grooved runways. As a result, a new industry has evolved that is based on the scientific and technological advances of the Langley research. Approximately 2,000 people are presently employed in the industry, and five companies manufacture the specialized equipment for grooving. These firms have formed a trade association, the International Grooving and Grinding Association, to promote grooving at the international, federal, state, and local levels (Reinhardt, 1972).

Commercial and military aviation. The evolution of control systems technology under NASA auspices has reached a point where it has become possible to achieve fundamental changes in both aircraft design and a wide spectrum of complex industrial control systems. The "digital fly-by-wire control" first used in Gemini and Apollo spacecraft eliminates conventional, direct mechanical and hydraulic linkages between the pilot and vehicle control surfaces. This change was brought about slowly, beginning with hydraulic boost for conventional controls used twenty years ago in the T-33, B-47 and commercial transports. The next step was fully powered hydraulic controls used in the F-86, century series fighters and large transports. The F-4, F-104, F-102, and other high performance aircraft were fitted with stability augmentation systems in which motion sensors augmented pilot response. The next generation channeled inputs from the pilot through the motion sensing system that was used in the F-111, B-70 and the C-5. The penultimate version of this technology was incorporated in the X-15, Concorde SST, and Mercury spacecraft as a pseudo fly-by-wire that allowed the pilot the option of conventional controls. Finally, with the X-20 and Gemini and Apollo spacecraft, a pure fly-by-wire system appeared in which the pilot's control inputs are sensed by position transducers and transmitted to a digital computer (the Apollo Guidance Computer), as well as to a triple redundant backup system which provides a means of direct control in case of primary system failure. The guidance computer calculates the desired response of the vehicle and compares it with the actual aircraft motion. The computer then signals control surface corrections that will change the actual motion to conform to the desired motion of the vehicle. Such signals are carried by electrical circuits, thus the term "fly-by-wire."

The digital computer, which was developed on the Apollo program, has several vital functions. First, it provides control augmentation under normal operation. Second, the system contains built-in logic to assure that the pilot control inputs follow the basic control laws of aerodynamics. Third, the computer contains a proven fault detection and recording capability which monitors the operation of the entire digital system, including the computer itself, the coupling data unit, and the inertial measuring unit. If a malfunction is detected in any of the hardware or software components, the control system switches to the redundant backup system operated by the pilot.

There are several advantages to the fly-by-wire system over conventional control systems. By eliminating the mechanical linkages between the pilot and the control surfaces, there is a considerable saving in weight. For military aircraft, in particular, the presence of a triple redundant, electrical backup system provides greater security against the loss of control caused by localized damage. Finally, if fly-by-wire control is used, there is no longer an overriding need to design for an aerodynamically stable vehicle which could be handled despite control failure. By obtaining an equivalent level of control reliability in other ways (e.g., error detection, backup redundancy), the fly-by-wire system frees the designer to use aerodynamically unstable designs that can provide increased lift and reduced drag, thereby improving aircraft performance.

The feasibility of a whole new field of control-configured vehicles (CCV) is being explored because of fly-by-wire technology. Large aircraft, among others, may be designed differently: they may be designed for strength rather than stiffness; wing weight can be reduced five percent by altering control surfaces to shift lift distribution inward; and tail surfaces can be reduced in size by as much as 50 percent. All of these changes contribute toward a potential weight reduction of 20 percent for new large aircraft. The final impact of this technology and the importance of NASA's demonstration of feasibility are not yet clear. The United States Air Force, however, has begun an experimental program to evaluate CCV (Yaffee, October 16, 1972).

The great significance of the fly-by-wire control system concept to industrial practice lies not only in its anticipated revolutionary change to aircraft performance and reliability, but also in its potential secondary utilization for a broad range of industrial controls. The concept simplifies linkages, reduces maintenance, and achieves greater reliability by allowing an inexpensive addition of redundance to control system linkages. The simpler, more reliable form of control is very appropriate for complex mechanisms such as helicopters and hovercraft and also seems well-suited for industrial cranes, high speed ground transportation vehicles, automated manufacturing machinery, and other complex industrial devices.

Several contractor organizations have joined NASA Flight Research Center engineers in the fly-by-wire development program. These include Sperry Rand, Massachusetts Institute of Technology, Delco Electronics, Hydraulic Research and Manufacturing Company, and Ling-Temco-Vought. Currently, attention is being given to the commercial application of the fly-by-wire concept (Delts and Szalai, 1972).

Perspective. These four examples were chosen to illustrate diversity in the ways that firms can gain through the conduct of mission-oriented development work. At the same time, these examples illustrate how technical improvements flow into different patterns of products and services which comprise American industrial progress.

MODE IV: Intersectoral diffusion of technology generated through long-term basic and applied research and development in materials, apparatus, and processes by the dissemination of results through professional societies, industrial design codes and published documentation.

The Lewis Research Center has been responsible for much of NASA's work in the field of rotating equipment. This field represents one area of research that has strong ties to the industrial world because prime movers (i.e., motors, generators, compressors, turbines, and engines) permeate almost every industrial classification. Industry is broadly concerned with the scientific and technical developments which effect the performance of rotating equipment, as well as the new options in the use of rotating equipment to do useful work. In this regard, an aircraft turbine engine was first coupled to a generator to produce ground-based electrical power twelve years ago (Electrical World, 1972). The construction of turbo-generating equipment is now an industry in its own right.

This commonality of technical interest provides one of the most powerful mechanisms for the diffusion of aerospace technology into industry because individual technical people from different economic sectors share in the advances made in a field through their participation in professional societies. These societies bridge economic and industrial sectors because individuals from different sectors are associated in the consideration of common technical problems such as lubrication, wear, corrosion, efficiency and material properties. Improvements in these problem areas are at the heart of the incremental improvements in equipment design and performance.

Technology diffusion through professional activity. The American Society for Testing and Materials (ASTM) is an international, nonprofit, technical society devoted to the promotion of knowledge on engineering materials, the standardization of specifications, and the standardization of test methods. In 1970 alone, over 190,000 volumes of ASTM standards were sold to engineers, scientists, and architects concerned with specifying and evaluating materials of all kinds.

At the heart of the society are the ASTM technical committees. Through these voluntary committees, ASTM coordinates a broad range of investigations leading to a better knowledge of the properties of materials; approximately 4,000 widely used standards have evolved as a result of these activities. Presently, the more than 100 technical committees of ASTM form the working groups in which current research is reviewed and appropriate standards are developed. The common denominator unifying each committee is a professional concern for a specific technical problem imbedded in the discipline or technical interest of a larger professional community. Such committees represent aligned communities that have memberships cutting across traditional intersectoral boundaries. It is through these communities that new technology is introduced in other sectors and further diffusion occurs.

An examination of the development of fracture toughness test methods over the past decade reveals how new technology affecting the safety and reliability of critical structures was developed and how diffusion was started by engineering practice. After years of education and experience, which relied on the assumption of a defect-free material, the design engineer now is forced to acknowledge the presence of flaws that can cause high-strength materials to fail in a brittle manner. In this situation, the problem becomes one of assessing the actual integrity of a material in the context of its intended use. Herein lies the domain of fracture mechanics.

Interest in fracture mechanics has been keen, but what engineers lacked was a quantitative way of relating a material property to the design of structures containing ever-present flaws. Early in 1959, at the suggestion of the Department of Defense and the National Academy of Sciences, ASTM organized an ad hoc committee to study the problems of brittle fracture. Their first task was to develop a qualitative test method that would permit rational selection of steels and design loads for the Polaris rocket motor case and, thereby, put an end to a continuous series of failures that threatened national security.*

What started out as a special committee, charged with the resolution of a specific problem, has grown to be a vital force in the fracture mechanics community. Since the resolution of the

*Joining researchers from the Naval Research Laboratory were members of the NASA Lewis Research Center and representatives from industry.

rocket motor case problem, the ASTM Committee E-24 on Fracture Testing of Metals has worked to advance knowledge in the field of fracture testing by:

- Promoting research and development on methods for appraisal of metals;
- Developing recommended practices, methods of test, definitions, and nomenclature for fracture testing of metals, exclusive of fatigue testing;
- Sponsoring both independent and cooperative technical meetings and symposia; and
- Coordinating the committee activities with those of other relevant ASTM committees and other organizations (ASTM, 1970).

With these activities serving to consolidate a community of interest, it is now possible to examine how a technical contribution of the civilian space program moved through the technologically aligned community to impact other sectors. NASA's concern for minimizing the weight of flight systems has also led to the extensive use of high-strength materials, and the performance of these materials is sensitive to the presence of flaws. To define this sensitivity, researchers at the Lewis Research Center developed the "plane strain fracture toughness test," and engineers for the first time could quantitatively determine the weakening influence of cracks in selected structural materials (Shannon and Brown, March 5, 1970).

Early dissemination of information on the plane strain fracture toughness test was primarily accomplished through the E-24 Committee via personal contacts and ASTM Special Technical Publications. In fact, before the test was finally incorporated this year in the ASTM Standards (ASTM Standard Test Method E 399-72), designers of critical structures had already adopted the test as part of their "best practice," thus accelerating the introduction of the innovation in other sectors.

Early adopters of the plane strain fracture toughness test were individuals with specific problems for which the conventional strength of materials approach offered no solution. Engineers at Westinghouse, for example, conducted extensive research to facilitate the application of fracture mechanics to power generating equipment. Fracture toughness data and fatigue crack growth rates were generated for commonly used pressure vessel materials--namely, ASTM A533 and ASTM A216. Plane strain fracture toughness values were determined over a wide range of temperatures for several specimens and weld metal using the NASA innovation (Wessel, 1969). Major efforts were also devoted to the determination of fracture toughness for common rotor alloys over a wide range of temperatures and strain rates, as well as for fatigue crack growth rates as a function of stress intensities. The basic alloys (A469, A470, A471) evaluated by Westinghouse are now employed in virtually all large turbine generator rotors and disk forgings manufactured in the United States (Greenberg, _et al._, 1969).

The design of the new Air Force/North American Rockwell B-1 strategic bomber has also relied heavily on the concepts of fracture mechanics. As a direct result, North American Rockwell (NAR) has stated that the B-1 design service life is now considerably longer than for any previous bomber. Titanium plate, produced in 15- to 20-foot sections, is required to have fracture toughness values determined in both longitudinal and transverse directions, at a cost of $300 per test. NAR will determine fracture toughness values on any material that undergoes processing after being delivered by a producer (_Aviation Week & Space Technology_, July 26, 1971).

Different kinds of adoption patterns for fracture mechanics are now appearing. Producers of primary metals, such as Aluminum Company of America, have found a growing number of customers demanding guaranteed minimum toughness values for the materials they purchase (Kaufman, 1971). In a typical response to similar demands, U.S. Steel conducted a program to determine plane strain fracture toughness of at least eleven commonly used steels (Rolfe and Novak, 1970). The significant diffusion characteristic exemplified here is that the burden for determination of fracture toughness data has started shifting from users such as Westinghouse and North American Rockwell to the primary producers of structural materials. Formalizing of the plane strain fracture toughness test by ASTM has greatly facilitated this transition. It can now be seen that the technology is moving into important areas of commerce and production, and this movement is being reinforced and accelerated through the formal training of new engineers at a growing number of institutions.

Based on the recommendation in the 1972 American Society of Mechanical Engineers Boiler Code Addenda, manufacturers of nuclear pressure vessels will now use experimental toughness values to design these vessels. This recommendation incorporates the results of extensive fracture toughness tests on pressure vessel steels conducted as part of the Heavy Section Steel Technology Program at the Oak Ridge National Laboratory.

The role of the professional community in the introduction of new technology is clearly evident: the early diffusion of the fracture toughness test not only is occurring within the aerospace sector (the B-1 materials evaluation), but it is also diffusing through other sectors where the safety and reliability of critical structures are paramount.

Industrial design codes. During the last decade, the increased performance in many energy conversion systems such as turbines and nuclear reactors has been due to higher fluid operating temperatures in the mechanical systems. The advances in reliable, high temperature (above 800°F) operating capability are dependent on material advances and better design data. The latter is particularly important in designing a system to provide reliable performance with a minimum of downtime and repair costs.

During the 1960's, there was a marked increase in the research effort aimed at providing a better understanding of the time-dependent mechanical and metallurgical behavior of structural materials under cyclic loading conditions at high temperatures (Berling and Slot, 1969). The Lewis Research Center had been investigating high temperature fatigue behavior of materials since the early 1950's. In particular, researchers at Lewis were the first to recognize that local strain, rather than local stress, causes high temperature fatigue in a material. Through the years, investigators at Lewis have participated in the numerous professional activities sponsored by the American Society for Metals, the American Society for Testing and Materials, and the American Society of Mechanical Engineers. By serving on professional committees, providing test data and computer time to committee activity, and presenting technical papers both here and abroad, results of the center's materials programs have been disseminated to engineers throughout the world (Manson, 1972).

One example of the wide-spread impact of this effort is found in the design codes published by the American Society of Mechanical

Engineers (ASME), which provide the criteria for receipt of the ASME Code Stamp. In some cases, this stamp is required by law for certain classes of operating equipment, where failure would have serious consequences. Lewis personnel have served on the ASME Subgroup on Elevated Temperature Design for many years. In 1964, ASME published a high temperature code (Code Case 1331) to provide design criteria for materials operating in conditions above 800° F. This code case has undergone seven revisions as advances have been made in the understanding of high temperature fatigue. In 1970 the linear life-fraction damage rule was adopted into the code case as a means of assessing the combined damage from creep and fatigue. This rule was first proposed about 20 years ago, but it lacked credibility until extensive tests were conducted at Lewis to demonstrate that it worked as a useful property estimator (Halford, 1972).

Since 1970, a more sophisticated technique, called strainrange partitioning, has been developed and verified at Lewis. This technique greatly simplifies the testing and analyses required by the linear rule, since the variability of the creep test data is reduced. A position paper has been prepared at Lewis to present this new technique to the ASME Subgroup on Elevated Temperature Design for possible adoption in the eighth revision of Code Case 1331 (Halford, 1972).

In its present form Code Case 1331, or its equivalent data, is applied as a critical design parameter for high temperature gas reactors, liquid metal fast breeder reactor development, steam boilers and boiler tubing, gas turbines, and other high temperature mechanical systems.

Published documentation. NASA has maintained a continuous and basic interest in certain technical fields which are also advancing through industrial research and development activity concerned with nonaerospace application. These fields can be characterized by their disciplinary nature (i.e., heat transfer, fluid flow, strength of materials) and the fact that basic advances in the field oftentimes have great impact because of the technology being common to many applications. In this regard, one particular NASA research effort and the ways it has affected design, operations, and industrial practice will be examined.

The combustion of high energy fuels has long been of interest to NASA, as well as its predecessor the National Advisory Committee for Aeronautics (NACA). The performance characteristics of turbine and rocket engines are derived from the combustion processes; in turn, the performance of the vehicles powered by these engines is also defined. The Lewis Research Center has conducted combustion research for more than 25 years. One result of this effort was the development of a computer program in 1961 that allowed the calculation of complex chemical equilibrium compositions for use in chemical systems.

Knowledge of the chemical equilibrium composition permits the determination of the theoretical thermodynamic properties for the system--a solution needed for a wide variety of problems in chemistry and chemical engineering. Some applications are in the design and analysis of equipment such as compressors, turbines, nozzles, engines, shock tubes, heat exchangers, and chemical processing equipment (Gordon and McBride, 1971). Because of the wide interest in the original program, it was modified, rewritten, and improved through the years, with the most recent version being available since 1967. The programs are known as the NASA-CEC series.

During the last five years, almost 200 scientists and engineers from universities and commercial firms have requested the latest program from Lewis. One area of application that is particularly significant now concerns the use of the program as a tool in pollution control.

The Phillips Petroleum Company became aware of the program through a conference on high temperature research that was held at Lewis in 1969. The company presently uses the program to analyze combustion processes in automotive pollution control experiments, where they are concerned with nitrogen oxides (NO_x) and carbon monoxide (CO) emission. By slightly modifying the program, it has been possible to analyze various fuels and fuel combinations combusted in an engine operated at different compression ratios. In addition to aiding in the blending of gasolines for pollution control, Phillips has used the program to develop tables on the combustion equilibrium for various fuels; and, in its consulting work, for analyzing the effluent of incinerator plants and pollutants from waste gas flaring (MacQueen and Lee, 1972).

The Continental Motors Division of Teledyne, Incorporated is attempting to adapt the program to provide combustion simulations for turbocharger analysis. These studies will aid in the design of small aircraft engines which now must meet the federal pollution regulations for NO_x and CO. The investigator in the research effort became familiar with the program through his work at the Florida Research Center of Pratt and Whitney, where it was used extensively in rocket combustion and jet engine combustion analysis. He further stated that the NASA-CEC programs are the standard in the industry for such analyses, and the National Bureau of Standards uses it as a reference program (Sutherland, 1972).

The Babcock and Wilcox Company obtained the program from Lewis about two years ago. The company uses it regularly in design studies for fossil-fired boiler modifications to reduce NO_x emissions and for sulfur recovery processes for several sulfur dioxide (SO_2) cleanup systems that are being developed for power plant exhaust gases. Babcock and Wilcox engineers analyze the operating trends for different hardware configurations with the program so that guidelines leading to experimental design improvements are established.

Perspective. These three examples illustrate how the movement of technology is achieved in an informal sense through the professional activities of individuals. One important factor of this type of technological progress is that the problems addressed are extremely difficult, with no simple answers. In this way, NASA adds to the body of basic knowledge and draws from the additions of others.

MODE V: Relocation of skilled individuals from aerospace employment to employment in a different economic sector, resulting in adoption of aerospace technology to solve analogous problems encountered in the new sector.

Since 1960, an entirely new technical field, contamination control, has been created to help satisfy the high reliability requirements in the aerospace and atomic energy industries. NASA, the AEC, and the Department of Defense were instrumental in this classic example of new demands converting an old art into a new science. Although the art of contamination control has been practiced for many years in hospitals and industries such as food processing and pharmaceuticals, the intensive federal R & D programs of the last two decades have created the modern technical field of contamination control, complete with its own equipment manufacturers, professional societies, and an integrated technological base. The experts and manufacturers that comprise the contamination control industry are strongly diversifying to satisfy a growing demand for better product quality and public health in many sectors of the American economy (Whitfield, 1970).

The space program, with its high reliability and oftentimes sterility requirements, provided a major "first market" for advanced contamination control equipment designed to NASA specification. This first market contribution to the industry facilitated rapid growth in production capacity, consolidation of equipment standards, and sophisticated product design capability. One result has been that the contamination control market has experienced steady growth in spite of a drastic reduction in aerospace sales. Four major producers of one important type of contamination control equipment--laminar flow units--were surveyed in 1971 to discover the changing market for their products. Their aggregated sales have continually increased since 1960, and the percentage of sales to nonaerospace customers has grown from almost nothing to approximately 90 percent (Denver Research Institute, 1971).

In addition to providing a major market for contamination control equipment, NASA generated two cornerstone documents: SP-5045, Contamination Control Principles and SP-5076, Contamination Control Handbook. These two publications conceptualized the principles of contamination control and described the methodology of its practice in detail.

The diffusion of contamination control technology across different sectors of the economy has occurred not only through the processes of technical and market integration, but also in a significant way through the movement of people. Prior to 1965, most modern contamination control experts were employed in the aerospace industry. In the mid-1960's, however, the first shift in employment took place, with many experts moving to new application areas in the computer and pharmaceutical industries. Presently, almost all pharmaceuticals and many computer components are produced in clean rooms that are the direct descendents of aerospace facilities. A second major shift in employment is now occurring as new or expanding applications in other industries, such as experimental animal laboratories, dairy products, consumer product electronics, cosmetics, and automotive components, have created an expanding job market for contamination control personnel from the aerospace programs (Hite, 1972).

One example of employment change for contamination control experts that illustrates the resulting technological change for the employing company involves the case of Ronald R. Hite. Hite developed his expertise while working for the Hughes Aircraft Company. In 1967 he participated in the preparation of a section on clean packaging for NASA SP-5076. Hite has also been a member of the American Association for Contamination Control since its inception and has served on its board of directors as chairman of the Publications Committee. In 1968 Hite joined the staff of Scientific Data Systems, Incorporated as a contamination control expert. The company, now called Xerox Data Systems, manufactures computer peripheral equipment such as disc file memories and tape drives. Since joining the company, Hite has used his experience in aerospace contamination control techniques and the two NASA documents cited above to make several improvements in the control of contamination in the company's production facilities, including faster and more thorough cleaning techniques, cheaper equipment to achieve the same or higher cleanliness standards, additional clean work stations, and improved monitoring of contamination control equipment. As a direct result of these improvements, Xerox Data Systems has significantly reduced the failure rate of finished products during quality control inspection, increased the production rate by doing a more thorough cleaning job in less time, and reduced the overhead costs for contamination control equipment and operation. Hite is also a consultant for several other companies, including Philips Industries of Holland. This example is by no means unique in the contamination control field. Contamination control experts are constantly developing new applications for saving money, increasing reliability and reducing health hazards (Hite, 1972).

In a larger sense, the impact of people movement can be seen in the experience of KVB Engineering, Incorporated, a California consulting firm founded in 1970 which specializes in pollution control for electric utilities. The key personnel in the firm have strong ties with NASA combustion research through prior employment with NASA contractors, where they contributed directly to advancements in the state-of-the-art. This experience has propelled the company to a position of leadership in combustion engineering research. One of the most significant accomplishments of the company's consulting work has been the practical demonstration that nitrogen oxide emmissions from power generating plants can be reduced by 40 to 50 percent through tailored changes in boiler operating procedures, changes that do not introduce the risk of hazardous combustion conditions or gross inefficiencies within the boiler. KVB has undertaken analyses for nine major utilities and is playing a crucial role in the reduction of power plant pollution, particularly in the Southern California area (Breen, 1972).

Perspective. Contamination Control is just one field in which people have acquired expertise while performing indispensible tasks in the space program. Other fields, such as nondestructive testing, welding, and management, could also be used to illustrate how increased ability, acquired during a venturesome program such as Apollo, is being employed in other sectors of American industry. For example, the Tennessee Valley Authority, in selecting new employees for welding and nondestructive testing, places high priority on personnel with aerospace experience (Willis, 1972).

MODE VI: Public-interest transfer of space program experience to nonaerospace organizations through a planned program linking the NASA/aerospace sector with commercial firms and public sector entities.

In the elaboration of the various modes for technology utilization presented thus far, there has been a common element: the adopter has been aligned in some way with the aerospace sector, either professionally or contractually. This type of relationship provides a driving force for the movement of technology simply because such firms and individuals have been involved in the generation and first application of new technology. But what about the nonaerospace sector? How does a firm participate in the gains from aerospace research and development without being a part of that sector?

NASA has developed a formal program to facilitate technical interactions between aerospace and nonaerospace sectors. This program was energized, in part, by a NASA policy for systematically documenting the occurrence of and conditions attendant to invention or innovation during the conduct of aerospace R&D. The basic mechanism operating in the contractor's sphere is called the "new technology clause," which requires the disclosure and description of each invention or innovation discovered during the contract work. These contractor disclosures, together with similar inputs from R&D conducted by Agency personnel at the NASA research centers, are evaluated. In the case of invention, patent applications are prepared to aid in the subsequent license of the development by firms interested in bringing the technology to the marketplace. Whether inventions or innovations, these developments are brought to the attention of the industrial community through the programs of NASA's Technology Utilization Office.

The Technology Utilization Office operates various programs to effect the transfer of aerospace technology. In addition to its publishing program, which has several different experimental forms, there is a program which links business and industry directly with the store of aerospace technology (Regional Dissemination Centers); a program which provides an interface between aerospace and public sector problem areas (Technology Application Teams); and a program which provides adaptive engineering in the solution of specific public sector problems. The publishing program and the dissemination centers have been particularly successful in linking the aerospace and nonaerospace industrial sectors to influence engineering design, new and improved products, and process improvements. These programs will be illustrated through documented transfer examples.

The publishing programs. In order to meet different objectives and user needs, NASA's publishing programs have taken two main forms. One series--Special Publications--reviews significant technical developments in a state-of-the-art context for specific technical fields. More than 200 of these reference works have been prepared and disseminated through the Government Printing Office and the National Technical Information Service.

Perhaps more widelyknown is the Tech Brief. Tech Briefs are essentially abstracts of technology that are distributed widely through NASA mailings and through the new technology program of the Small Business Administration. When the Tech Brief alerts a potential user to a technological development, the user may request more detailed information in the form of a Technical Support Package (TSP) or be placed in contact with the technology innovator. Approximately 5,000 Tech Briefs have been published since 1963, and more than 100,000 requests for TSP's have been made during the past 12 months alone. The following examples illustrate the kinds of applications stimulated by the Tech Brief-TSP program.

A Technical Support Package which describes a method for predicting the biaxial weld strength of welded structures was used for redesigning pipes in an Eastman Kodak Company chemical plant. Previously, pressure surges in the chemical piping produced ruptures that created serious safety problems. A design engineer working on the problem requested the NASA document after seeing the Tech Brief. He used the prediction method that was outlined, in conjunction with failure analysis, to develop the pipe designs which were incorporated in new installations. Plant safety has been significantly improved by eliminating rupture hazards, with relatively little cost to the company (Winter, 1971).

After receiving a Tech Brief on a potential anti-fog coating compound, several companies and individuals obtained NASA licenses to produce and sell the compound. Each licensee found an immediate market for his new product in such diverse application areas as ski and swim goggles, firemen's masks and standard prescription glasses.

No technical adaption of the NASA technology was required; and the only developments needed were production capability, packaging and a distribution strategy. For most of the adoptions, the new product complemented an existing product line (Denver Research Institute, 1972).

Gannett, Fleming, Corddry, Carpenter, a civil engineering consulting firm, is using a TSP that describes workmanship standards for fusion welding to evaluate flood gate welds on flood control dam projects in Pennsylvania. An engineer with the company requested the TSP for this purpose after seeing the Tech Brief. On the Foster Joseph Sayers Dam Project, the evaluation allowed a cost savings of more than $200,000 through the substitution of equally suitable, less costly, steel alloys (Seip, 1972).

Rancho Los Amigos Hospital has pioneered in adapting aerospace technology to its work in caring for and rehabilitating chronically disabled persons. The various technologies of miniaturization have proven quite important in designing advanced power and control systems for orthotic and prosthetic devices at the hospital.

The most recent transfer of NASA technology at the hospital involves a small piezoelectric transducer that was developed under NASA contract by two University of California scientists and described in a Tech Brief. The invention consists of a hybrid thin film and a piezoelectric transistor that acts as a pressure-sensitive device with built-in signal amplification. A hospital staff scientist encountered the Tech Brief while working on an oral control concept for paralyzed patients to use in controlling wheelchairs and powered orthotic appliances. A tongue-operated, multichannel control system, held on a bracket in front of the patient, is the current approach. Contact with the inventor of the new transducer led to applications engineering support from the Technology Utilization Office to adapt the device for use in the intra-oral control system. Prototype models have been built, and a major electronics manufacturer has taken steps to perfect mass production processes for making the transducer and the associated integrated circuit components (Bontrager, 1973).

Regional Dissemination Centers (RDC's). The five Regional Dissemination Centers supported by NASA help users obtain technical information in packages that are tailored to their specific needs. The RDC's primary information source is a computerized data base of over 800,000 scientific and technical aerospace reports. This data base is supplemented by abstract services in specific areas such as chemistry, engineering, electronics, plastics and metallurgy. The services of the RDC's can be seen in the following transfer cases.

Many companies in the electric power industry have utilized RDC services to help fill their scientific and technical information needs. The Western Energy Systems Transmission (WEST) Associates is a consortium of 24 power companies formed to promote interaction on common problems. For over two years WEST has had an on-going program with the Technology Application Center (TAC), the NASA RDC located at the University of New Mexico. TAC has provided WEST with retrospective searches and monthly current awareness information concerning the areas of air pollution and water pollution. Specific searches on topics such as "Fly-Ash Utilization" and "NO_x Detection and Abatement" have also been prepared for individual members of WEST (Long, 1973).

Most often, companies call upon the RDC's to provide information on a particular problem. Pyronetics, Incorporated was developing a portable, low-cost, multi-purpose welding torch, but was confronted with the problem of a bulky, high pressure oxygen supply. In March 1971, Pyronetics requested a retrospective search of the NASA data bank for information on chlorate candles. These candles are unique in that they generate oxygen while burning. The Western Research Application Center (WESRAC), the NASA RDC located at the University of Southern California, provided information on composition, hazards, applications, manufacturers and shipping regulations. This information was crucial in the development of Pyronetics' new, portable welding torch, which weighs only seven pounds and sells for approximately $40. By the end of 1972, over 20,000 units had been sold (Tierney, 1973).

Perspective. While NASA's efforts to document and disseminate information have been of central concern here, the Technology Utilization Program also has other dimensions: Technology Application Teams, computer program dissemination and adaptive engineering efforts. The unique characteristic of all of these program elements is that they operate to provide technical assistance for problem solving; and, furthermore, they represent planned efforts on the part of the Agency to provide assistance to people not normally aligned with the space program.

SUMMARY

This profile of the modes for technology utilization shows the pervasiveness of the transfer and diffusion of aerospace innovation. It has been demonstrated that major aerospace research and development firms have internalized specific experiences and embodied these experiences in new commercial and industrial products; specification, standards, and quality assurance requirements have carried over to improve the reliability of commercial manufacturing; manufacturers have found new applications and markets for their aerospace-related products; basic developments in scientific and engineering disciplines are being incorporated in industrial equipment design and construction; relocation of skilled individuals is helping to infuse aerospace-generated techniques and practice into different economic sectors; and, finally, systematic identification, documentation, and dissemination of information concerning aerospace innovation has stimulated extensive adaptation activity by persons and organizations in both the public and private sectors. While a myriad of examples have been cited, a much larger question can be asked: what does all this activity mean in the aggregate? In a recent comprehensive study that was undertaken for NASA by Midwest Research Institute, quantification of the relationships between technological progress and economic growth was undertaken. Among the major findings were:

- During the period of 1949 to 1968, the technology added to the nation's production recipe accounted for 40 percent of the real increase in private, nonfarm output;

- The leverage applied by technological progress on the total stock of labor and capital permitted almost 20 percent more output than otherwise might have been achieved with the same quantity of labor and capital; and

- Assuming that NASA's R&D expenditure had the same payoff as the average, the $29 billion spent during the 1959-1969 period have returned $56 billion through 1970 and will continue to produce payoff through 1987, at which time the total payoff will have been $207 billion (Midwest Research Institute, 1971).

The examples and modes of technology utilization presented in this document show how the aggregate economic and productive gains cited above are actually achieved.

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