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The Potential of Space Manufacturing

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THE POTENTIAL SCOPE OF SPACE MANUFACTURING

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ABSTRACT

This paper defines space manufacturing, then discusses the potential processes and product types that are implied in the definition. Both current government early planning and commercial industry formulative thinking contribute to the definition.

How quickly space processing or space productization occurs is directly tied to critical technologies, legal implications, and business incentives.

A roadmap to space manufacturing is offered. It sets forth the time phased events that must occur in the near term 1982-1987 to cause space manufacturing to be commercially profitable in the 1990's. The key to any attempt at scoping the promise of space manufacturing is the timely involvement of the private sector in space activities. The cornerstone of this involvement is the need for strong government commitment, backed by funding, to the concept of promoting United States commercialization of space for national benefits.

INTRODUCTION

The possibility of industrializing outer space is one of the most exciting concepts of the U.S. space program. Until now, our efforts in space have focused on scientific research, exploration, and support of military needs. With firm success in these areas, we are now ready to consider the prospects of practical space industrialization. The word itself - industrialization - denotes a new vista of thinking for space projects. To discuss industrialization, we must use terms such as production of goods and services, manufacturing equipment, labor force, competition, return on investment, products and markets and risk. These terms are well known to earth businessmen, but for space planners they portend a new way of looking at future projects.

Among suggested space industries are electric power stations in space that would supply earth; public service platforms for communications; and space factories to make unique products and materials for earth or orbital use. These are, of course, in addition to satellites providing weather services, earth resources surveys, navigation services, and the relay of educational and entertainment programs.

SPACE PROCESSING OF MATERIALS

With much pioneering in space technology behind us, and the prospect of low-cost space transportation in the form of an operational space Shuttle ahead, it is timely to think about a stepped up effort in the United States to exploit space for social and economic benefits.

One area of space exploitation that could have significant importance to our quality of life, and also provide economic gain, is the potential of processing materials in space.

The United States Materials Processing In Space (MPS) Program, sponsored by the National Aeronautics and Space Administration (NASA), started in the 1960's from ideas motivated by engineering data which demonstrated the novel behavior of materials undergoing physical changes under the low gravity conditions of free fall or orbital flight. The basic thrust, even then, of these ideas was directed to exploiting such effects to the manufacture of unique new products.

The MPS program, as managed by NASA, now involves ground-based experimental and theoretical studies and space flight investigations to develop a comprehensive understanding of the role of gravity in materials processes.

The long range goal is to develop the capabilities, indigenous to space flight and the space environment, for materials research and processing to: 1) demonstrate these capabilities to the scientific and industrial communities, and 2) provide opportunities for independently funded users to exploit the space environment for materials processing applications related to their own needs.

To provide for transition from NASA to non-NASA space activity, NASA's program actively seeks to establish cooperative research and development (R&D) programs with other U.S. government organizations (e.g., Department of Defense and National Bureau of Standards), as well as joint endeavors with private companies to develop and commercialize space-based product applications.

WHAT IS SPACE MANUFACTURING?

The term "space manufacturing" should be used with care. It will be the outgrowth of materials processing in space which in turn refers to reduced gravity activities in five basic processing areas:

- Crystal Growth. There are three broad categories of crystal growth that are considered most conducive to in-space processing: growth from a melt, growth in solution, and growth from a vapor phase. The procedures involved will be strongly dependent upon the problems of positioning, stirring, and shaping the melts and solutions under weightless conditions.

- Purification/Separation. This area will benefit from in-space processing because of greatly reduced buoyancy and convective effects. The production of super-pure materials becomes possible when one can use high temperatures, ultrahigh vacuum, and containerless samples (especially in multipass molten-zone refining of ultrapure elements). Also included in this process area are low temperature separations of biological materials such as living cells, serums, vaccines, and other macromolecular materials of potential medical or pharmaceutical utility.

- Mixing. This process area includes procedures where homogenization of materials is a problem on Earth because of density differences that cause segregation problems upon solidification. This is apparent in two specific areas: immiscible materials and composite materials. On Earth, inhomogeneities are caused bv variations in: density and surface tension between the separate components.

- Solidifications. There are three areas included in this category: controlled or directionally solidified eutectic structures; preparation of glasses; supercooling and homogeneous nucleation.

- Processes in Fluids. This area consists of two types of processes as they occur under weightless conditions: chemical processes which are concerned with reactions and reaction rates, and physical processes which are concerned with physical and thermodynamic phenomena (not changes of state or compositions). The condition of very low gravity will permit evaluations that have never before been possible in these fields.

Ground and space research in these five areas will lead to precommercial demonstrations for applications to:

- Space-made products; ground-made products
- Products combining space and ground processing

Space manufacturing, at least before the year 2000, should not be thought of in terms of space-based factory type facilities where computers, wristwatches, home applicances, cold remedies, or television sets are produced in assembly lots. Space manufacturing does not envision use of the space environment for jobs better done on Earth; rather it involves taking advantage of the unique characteristics of space - particularly the aspect of weightlessness - to do useful tasks which cannot be performed as well, or at all, on Earth and to understand the gravity effects on Earth processes.

THE SPACE MANUFACTURING TIMETABLE

Space manufacturing of high-volume-per pound materials or products is a possibility for the 1990 time period.

A range of devices, from electronic components to medicines, could be made in space. The technology appears feasible, the economics look promising but many complex issues remain to be resovled.

Assuming the United States and certain international materials processing in space programs proceed as present planning indicates, we should witness, in the last decade of this century, the start of space commercial manufacturing conducted aboard large Earth-orbiting space facilities.

Space manufacturing will probably progress, Figure 1, in three phases - early flight research, process development for transition to commercialization, and, finally, space production. The flight research phase has already begun; a two-year program of drop-tower and aircraft tests in the late 1960s led to simple materials science demonstrations performed on Apollo flights. This ground-based research was expanded to provide some 14 experiments and nine materials science demonstrations on the Skylab and ASTP projects in 1973-75. The results of the ASTP and Skylab work were generally very good - in some cases, beyond expectations. Flight research will continue with experiments flown on sounding rockets to provide five-to-seven-minute periods of low-gravity operations until Space Shuttle flights begin in 1984 or 85.

The flight research phase has thus far centered around:

- Separation and purification of biological materials.
- Metallurgical processes such as growth of the two-phase eutectic alloys with a continuous, undisturbed, rod-like hard phase in the softer, matrix phase.
- Production of high-index-of-refraction glass by levitation.

The process development phase of space manufacturing the late 1980s to early 1990s will involve fundamental engineering and economic studies of materials behavior and space manufacturing equipment, and the design of pilot plant operations. This second phase will use continuing rocket flights, the Space Shuttle/Spacelab missions, possible free-flying automated spacecraft for special investigations, Space Platform with an attached Materials Experiment Carrier, and the Space Station. This work will require that scientists and engineers fly on board the Space Shuttle flights to satisfy their experimental objectives. It will be a period of emphasis on broad research studies rather than a single-point or random experiments-a time of very active learning about many processes and problems.

Progress in space processing as a discipline during this period will depend on how often investigators can obtain opportunities for short-duration flights from which experimental results can be quickly obtained and disseminated. As experience is gained, longer-duration flights will be desirable to more fully take advantage of the space environment. At some point during this phase we will definitely need continuous and permanent space facilities.

The third phase is industrial utilization and space manufacturing on space stations. This phase will emphasize productivity and economic return, and space industrialization will become more dependent on business and legal decisions than in prior phases. There will be continued process development on Shuttle/Spacelab flights; the use of space stations for manufacturing research, development, and pilot plant operations; and, finally, commercial production of selected products in space bases.

The above postulated time scale is meant as a scenario that might be achievable. Yearly level of government funding into the program, as well as technical events, will strongly modify the actual history of the program.

COMMENTS RELATED TO ALL THREE PHASES

Major issues and considerations must be addressed at various points as progress is made through these phases. Summarized, these issues pertain to answering the following questions:

- What products or services qualify for early commercial exploitation?
- How will proprietary data be handled? Patents? Tax Incentives?
- How much are the user transportation charges and who must pay these charges?
- What are the implications of international cooperation versus competition?
- When will space commercial production be economically attractive for private industry?

From the standpoint of commercial production, perhaps the most important decisions need to be made during the transition from research and development activities to pilot plant operations. The importance of this transitional stage, when the technological capabilities of a processing system have been demonstrated, but the user community is not yet aggregated, or has not yet had sufficient opportunity to try the system, is handing over the newly developed capability to a new class of operators. The transition implies duplication, for some period of time, of human resources - the "acquired" and the "acquiring."

Major emphasis throughout all phases will be directed toward applications which lead to production in space as justified by economic and unique demand considerations. Space processing production will grow as progress is made in: materials research, equipment maturity, host vehicle resources provided and market trends for product demand. Quantities of materials produced or samples processed will increase (as the space vehicle for space processing evolves) from laboratory operations to pilot plant operations to production plant operations.

Commercial industry will certainly wish to exploit the cheapest possible way to work in space. Highly specific facilities will be evolved and dedicated to individual product forms rather than general purpose capabilities which were appropriate to the prior phase. Use of Space Shuttle for transport, government space stations, or alternatives such as privately owned manufacturing complexes will be dictated by whether government financing or industrial risk capital dominates. Continued dominance of space access through government funding will have to be replaced by alternatives in an expanded industrialization era.

PROGRAM ASSESSMENT

I believe a sufficient body of ground research and flight demonstration data exists on the behavior and characteristics of materials in low gravity environment to selectively proceed into expanded materials experiments on Shuttle flights in the mid 1980s. Appropriate supportive research on earth is essential to the success of these efforts. While the promise of space manufacturing appears exciting and the experiment equipment and payload facility technologies appear feasible, many complex issues remain to be resolved.

The prospects of success with early year (1984) MPS payloads are good. Processing equipment development problems are understood and appear solvable at reasonable costs. However, the direction of progress in the immediate downstream MPS program is tied to NASA funding constraints, the character of research in evolving an applications program and on business, legal and government/industry issues which are now in the early stages of address.

Detailed engineering issues on MPS payloads for early year Shuttle flights are well documented in NASA contractor reports. They pertain to electric power, heat rejection, payload control, data management, equipment development, Spacelab/MPS payload interfaces, crew utilization and others.

A major question is whether space manufacturing can be a profitable business venture. The concept of space manufacturing is quite new; the product forms have yet to emerge, costs are uncertain, very little market analysis has been conducted and accurate cost-benefit evaluations are still required. These evaluations are complicated by the fact that they must take into account probable improvements in earth-based technology between now and the time space manufacturing can become a reality. There appears to be no severe technological problems, but industry needs answers to many questions about profitability, product mix, financing, supply and demand, public needs, liability, international implications, organization, product standards and government-industry obligations regarding proprietary data, Space Shuttle costs, and the availability of flight opportunities.

NASA must take the lead in the technology, providing resources of funding and flight opportunities and as discussed earlier, provide industry sufficient cause to be technically interested. Industry is capable of developing the body of business data specific to a projected product. The legal community working with industry and government must bring about the establishment of laws, policies and practices for extending industrial property rights in space.

Presently, NASA represents the most integrated management structure to lead the technology and provide a focal point of expression for industrial and legal participation. The American Bar Association provides a forum for collected legal activities for space law. At this time industry has no single focal point, and, consequently, must be addressed on a company-by-company basis. There is probably a role here that the Industrial Research Institute could play. NASA welcomes more active industrial participation in constructing the technology program.

The government policies on MPS are best expressed in the statement of NASA's Joint Endeavor program published in the Federal Register of August 14, 1979. This statement offers a first step in the way to handle industries' need for protection of proprietary data and to grant appropriate patent rights. Eventually some actual arrangements established in individual cases will be tested legally but for now the policy appears adequate. The Joint Endeavor agreements that have been effected give us positive expectations concerning NASA's desire and ability to negotiate agreements that will provide industrial proposers most of the protection and incentives that they need and to adequately define the roles of the two parties. The Joint Agreement policy also attacks the problem of flight costs on the Shuttle during early states of a commercial project. Methods for assuring reasonable, frequent, flight opportunities will have to be developed. Much depends on the success of the Shuttle orbital flight tests.

A PLETHORA OF SPACE PRODUCTS

At present four product classes appear to offer a combination of technological readiness and market potential which warrants serious consideration for commercialization before the year 2000: pharmaceuticals, electronic devices, optical products, and advanced alloys. See table, page 5. Of course, the decision to produce these or other potential products still awaits early answers to scientific, engineering and business/legal questions.

Estimates of the total dollar volume of all space manufacturing vary widely from a product value of $200M to $1B per year starting in 1990 and going from these amounts to $25 to $50B per year by the year 2000.

POTENTIAL SPACE PRODUCTS

PRODUCT CASES	SOME POTENTIAL PRODUCT EXAMPLES
PHARMACEUTICALS:	ANTIHEMOPHILIS FACTOR VIII, ERYTHROPOIETIN, PANCREATIC BETA CELLS, AND LATEX SPHERES
ELECTRONIC DEVICES:	SEMICONDUCTOR MATERIALS, DETECTOR MATERIALS, X-RAY TARGETS, DIODES AND SOLAR CELLS
OPTICAL PRODUCTS:	LENSES, LASERS, FIBER OPTICS, CERAMIC WAVEGUIDES, ELECTRONIC SUBSTRATES, UNIQUE GLASSES AND NARROW BAND FITTERS
ADVANCED ALLOYS:	TURBINE BLADES, SUPERCONDUCTIVE MATERIALS, MAGNETIC MATERIALS, CORROSION-RESISTANT ALLOYS, NUCLEAR FUEL RODS, AND LUBRICANTS

THE SMOOTH PATH TO SPACE

Those involved in space processing research agree that a strong program should be a long-term, balanced effort, which will include ground-based experimentation to complement in-space investigations. During the remainder of the 1980s we must come to understand the process phenomena and how they influence materials properties. Fundamental studies in fluid mechanics and heat transfer, convection in the presence of weak forces, thermal conductivity, boiling, and condensation. Studies of solidification processes should include fundamental work on the homogeneity of solidified crystals grown under weak forces. Research on new glasses and crystalline ceramics should include fundamental studies of nucleation and crystallization, convection-free diffusion, behavior of particle and liquid suspensions, and deformation-free high temperature reactions. Studies of electrophoretic processes in space are unlikely to prove productive without extensive ground-based feasibility studies. One interesting research possibility is exploitation of the extremely high-vacuum region in the wake shield of the Shuttle. Use of this environment for the processing of materials by melting and/or vaporation is being explored by NASA.

WHAT WE CAN LEARN

Besides following the manufacture of better products, space processing facilities will also enhance our technical knowledge of materials behavior. The actual properties of many of our materials are far below the theoretical limit, and space-based materials research promises to help us come much closer to these fundamental limits than do efforts in earthbound laboratories. Space processing will also allow investigators to eliminate the gravity-induced effects on materials, allowing better fundamental studies of solidification, heat conduction in liquids and gases, phase transformations, the shape of the liquid-gas interface as controlled by surface tension, especially in temperature gradients, surface-tension-motivated flow, the dynamics of flames and combustion processes, the dynamics of froths, and diffusion in fluids in a temperature gradient.

FOREIGN ACTIVITY

Foreign countries currently involved in MPS include Russia, Germany, France and Japan. Their activities are proceeding at a rate that constitute a threat to the technological superiority of the U.S.

The Russian program is broad in scope, and benefits from greater funding (three to four times that provided for NASA's program). The emphasis in Germany is on industrial involvement, as opposed to the scientific orientation of the French program. Japan has an active MPS program. They had one experiment on Skylab.

NASA's policy for cooperation with foreign MPS activities is documented, and will undoubtedly be amended to reflect joint needs as time progresses. For the time being, concerns regarding undesirable technology transfer from the U.S. to foreign commercial interests conflicts with the need to acquire as much space flight experience as possible through shared arrangements within the rather limited budgets of the various separate free world programs.

BRIDGE BETWEEN SCIENCE AND APPLICATIONS

Industrial participants must share an awareness of the important problem facing NASA on how to effect a smooth transition between spaceborne materials research projects and application of the results to product forms. We have science at one end, commercial ventures at the other. NASA must find a way of causing, early in the MPS flight program, a balance and transition across this spectrum of interests. Industry, universities and other government agencies must help NASA to achieve the balance.

NASA and selected principal investigators want to fly "good science." Industrial managers want to fly "foreseeable applications." If the latter can't envision the direction the former will take, establishing and maintaining their interest will be difficult. So, a combination program is urged of basic science and directed applications research which will serve to stimulate the long term involvement of both interests. How to accomplish it, how to select and design the payloads to meet a wide range of science/applications objectives - these are major management decisions.

SPACE MANUFACTURING PROSPECTS

What is suggested in the NASA early year flight (Shuttle) program equates to basically a research and development concept. This is appropriate and must be accomplished before pilot plant or production run missions are undertaken. Commercial utility of product forms must be tested.

Private industry has already reaped some benefits from NASA sponsored space research: for example, fire retardants, miniature batteries, high temperature lubricants, light weight composites, Tang, illumescent paints, elastomers, medical therapeutic and rehabilitating aids, malfunction detection systems for the home/automobile, high speed information transfer systems, energy saver and conversion devices, security systems, waste control systems, and more.

Now the question can be asked: "How can wide segments of all industries make commercial use of the space environment" and perhaps when?

The technology to test material concepts and products in space exists to some extent now but is certainly being made more real with the Space Shuttle. The NASA objective is to examine the potential of a permanent, manned and/or unmanned earth orbital facility, Figure 2, to serve individuals and organizations whose research and application goals can be furthered by use of the space environment.

If there is one big deterrent to broadening industrial involvement in space, it is initial capital investment. Inside industry, the hardest decisions deal with capital investment. Because these front-end monies are very significant, special consideration must be given to this crucial issue. NASA understands this problem and has been investing seed monies in various materials technical disciplines and projects to develop the data from space experiments required for realistic capital investment decisions.

If a survey were taken of industry's views of the prospects for space manufacturing, the following statements would probably surface:

1. A broad-based program of space processing will be required to identify as many promising avenues as possible for eventual commercial and industrial exploitation. Therefore, it will be necessary for the space activities to adapt to changing methods and materials as iterative processes illuminate the most fruitful approach.

2. New apparatus and instrumentation will be required to support the projected space processing program -- during the Spacelab era and beyond.

3. As space processing moves from the research to the processes development to the industrialization phase, the roles of the Spacelab, Space Platform, and Space Station are essential to conduct the necessary operations.

4. The technical issues associated with space industrialization are important; but the concepts and requirements are straightforward, predictable, and will follow, in an evolutionary manner, the engineering developments and facility configurations from previous space projects.

5. Cost-benefits evaluations are currently unreliable and will not yet allow definitive selection of commercially viable products for manufacturing in space -- attempts at improvement will continue, however, in order to secure funding support, new analytical methodology for product selection is vitally needed.

6. Space processing will require the endorsement of the industrial community in the 1982 to 1990 time frame if the technology is to become something more than a NASA novelty.

7. Basic questions of: data rights, proprietary activities, product qualification requirements, user charges for Shuttle payloads, space law, liability, taxation, and patent policies need clarification.

8. Government patent policies as a general rule are not liberal enough to encourage private initiative to take advantage of new technology as a result of R&D. Where investment and risk is high, as in the pharmaceutical industry, any company or group of companies would have serious reservations about investing its funds to research, develop, test, product and market a product for which an exclusive position cannot be maintained to assure adequate return on investment inherent in commercializing an ethical pharmaceutical. Already, government policies impact so heavily on industry that it is difficult even to assess the return of current investments.

9. A legal prerequisite to space industrilization can be met by modifying the present tax and intellectual property laws of the United States to cover space-based operations by U.S. corporations. Modifications offering incentives would encourage U.S. industrial participation in space research and manufacturing.

10. Processes and products of high social value may develop and sustain the space processing program before the appearance of profitable commercial applications.

Much of the above is depicted in Figure 3, the Ins of Space Manufacturing.

CONCLUSIONS

To date, about 200 United States companies have evidenced some interest in space based industrial research and manufacturing. So a constituency of space processing users and developers is starting to emerge. However, space industrialization will become a practical reality when private industry knows investment in space is technically possible, economically desirable, and legally permitted.

Specifically, technological development must identify products that can be advantageously exploited in space. These products must meet economic standards of return on investment, growth rate and total recoverable profit that place them within the limits of private industry's ability to undertake commercial development. Legally, the industrial investor must understand the jurisdiction under which his enterprise will operate. Particularly he must know the tax and patent policy regulations that apply to his endeavors.

Some space investment opportunities today meet all technical and economic requirements for investment by private industry. Unfortunately, however, space research demands extremely large capital investments that are best met by industry and government working together. Industry works for its eventual profit and government works for the welfare of the society.

Planning for space industrialization of materials processing has started with the identification of steps necessary to achieve commercial ventures. But active commitments by individuals and organizations are required to implement and sustain such an endeavor. In the face of some skepticism and the always present competition for resources, a spirited endeavor is called for.

Industry will look to the U.S. Government (NASA) for sufficient funding of early year (1982-1990) materials processing in space research in much the same manner that the government sponsored early development of the airplane and nuclear power.

A very important issue is the involvement of industrial participants as soon as possible in the applications area. Their technical progress and business motivations will then lead to the resolution of the other factors.

The need to combine skills of the scientific/engineering community with those of management in government and industry is apparent. To bring focus, to achieve a critical mass of endeavor and to incorporate industrial support is NASA's principal challenge. Industry must be enlisted to assist NASA in meeting this challenge.

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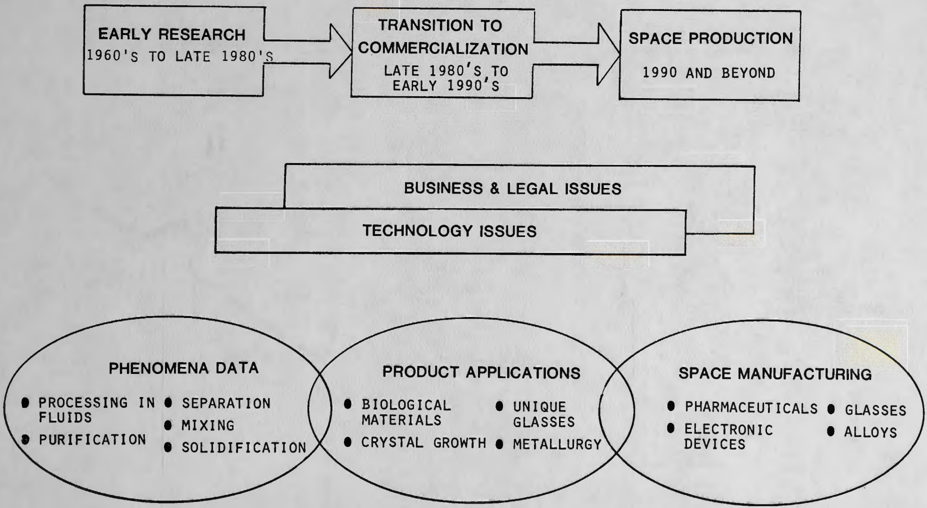
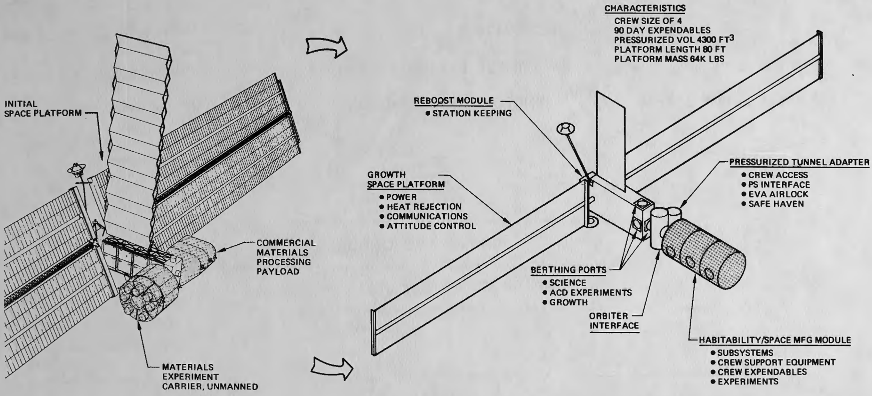


FIGURE 1. STEPS TO SPACE MANUFACTURING



SPACE PLATFORM WITH MEC AND A COMMERCIAL MATERIALS PROCESSING PAYLOAD

EARLY MANNED SPACE PLATFORM FOR INITIAL SPACE MANUFACTURING

FIGURE 2. REFERENCE CONCEPTS OF SPACE MATERIALS PROCESSING & SPACE MANUFACTURING

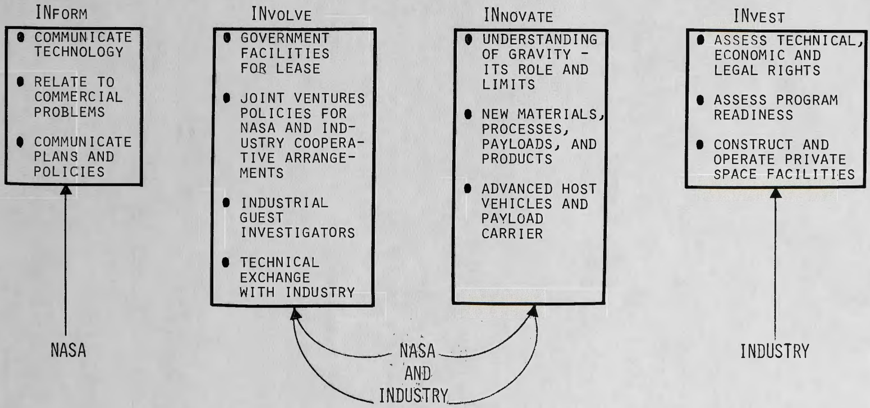


FIGURE 3. THE IN'S OF SPACE MANUFACTURING