STATUS AND PLANS OF NASA'S MATERIALS SCIENCE AND MANUFACTURING IN SPACE (MS/MS) PROGRAM

By William O. Armstrong and James H. Bredt
NASA - Office of Manned Space Flight
Washington, D.C.

Abstract

Following 2 years of relatively low-level exploratory work, the Materials Science and Manufacturing in Space program is now in a phase of expansion toward higher levels of effort. The main thrust of this effort is toward initiation of a research and development program on the Space Shuttle missions that can prepare the way for possible commercial manufacturing operations on permanently orbiting space stations. Experiment capabilities, currently being planned for the Space Shuttle, will be based on an inventory of reusable general-purpose equipment that can be configured in many different ways to meet individual experiment requirements. It is expected that this approach can support very large numbers of experiments and make flight opportunities accessible to many potential experimenters, who would not be prepared to involve themselves in the development of flight hardware.

Introduction

For ages man has dreamed of space as a new ocean to convey him out beyond the earth to the moon, the planets, and ultimately the stars. It is interesting to note that the spacecraft in these dreams were thought of only in terms of transportation. The spacecraft described by Jules Verne in "Journey to the Moon" and the ones used by Buck Rogers in his fascinating adventures were for travel in space. It is only recently we have begun to realize that orbiting spacecraft can provide other very important benefits for use right here on earth. Through use of spacecraft as an observation platform, many practical applications for space have evolved. They include such areas as meteorology, navigation, communications, and earth resources — to name a few.

Fairly recently, NASA has begun to explore a completely new field of applications, making use of properties of space to produce products impossible or prohibitively difficult to make otherwise. This new program had its genesis at the Marshall Space Flight Center (MSFC) where a few farsighted people began to discuss the possibilities of this new field of space applications with representatives of industrial organizations. Based on these contacts, two symposia were held at MSFC in 1968 and 1969 in which industrial concerns were invited to present ideas for using space for materials processing and manufacturing in space. Participation was excellent. Representatives of over 60 companies and research organizations attended, and 40 technical papers were presented at these two meetings.

With this encouraging beginning NASA started a program of research to build a technology base and explore promising possibilities for space research. This has grown from a limited effort of a few hundred thousand dollars in 1968, to a fairly subtantial research and development activity involving a number of industrial and research organizations, with funding in excess of $1 million per year.

Program Status

The results of these activities to date have convinced us that manufacturing in space is technically feasible and that space research in material science and technology is likely to pay off. As shown in Figure 1, one form of payoff can be expected in terms of useful scientific knowledge derived from space research, which improves our technological capability on the ground. This is likely to be the area from which benefits are initially derived and indeed may be the area of greatest long-term benefit as well. Eventually, however, we also expect returns in terms of products produced in space for market here on earth. Should they materialize, these returns will be very direct and tangible, because they will come in the form of profits on sales.

If we are to take space manufacturing seriously as a goal, we are forced to contemplate some grandiose objectives. The whole proposition makes economic sense only if we succeed in creating a space-manufacturing technology that can operate at a profit and if manufacturing operations go on long enough and reach a scale large enough to recover the investment that went in to making them possible. Obviously these are ultimate objectives rather than near-term ones. Our immediate goals are threefold, as outlined in Figure 2.

Extensive ground research is needed to understand the potential applications of weightlessness and other features of space well enough to know where the payoffs are. Therefore, an active and diverse program of in-house and contracted research is needed to build our technology base and identify promising processes for in-flight studies. Concurrent engineering development effort is also needed to define experiment techniques and flight facilities in which to conduct our space experimentation.

Our second goal is to expand the involvement of the scientific and industrial community at large. These are the ultimate users of our space capability and provide the best source of ideas for eventual utilization of space to solve their problems.

Finally, since the benefits of null gravity can only be realized in space, major program emphasis must be directed toward maximum utilization of spaceflight opportunities.

Since the thrust of our immediate effort is aimed toward meeting these goals, we will explore in more detail our current activities and future plans in each of these areas.

Buildup of the Technology Base

Recognizing the need for a sound technological base to underpin our future flight effort, the major emphasis of our present program is aimed at building this base. As previously mentioned, funding for this activity is now well in excess of $1 million per year and involves a number of in-house and contracted efforts (Fig. 3). The program is managed almost entirely from MSFC and is supporting contract studies in 17 outside organizations from a variety of different fields and interests. Eight tasks also are underway in-house at MSFC. It should be noted that nine additional tasks have been proposed for which support could not be provided.

As a result of our study effort so far, a number of promising areas have been identified, which eventually may prove economically attractive. Some of the most promising prospects are listed in Figure 4.

The possibility of levitating solids and liquids is one of the most obvious applications of weightlessness. Suspension of materials free of physical contact of containers should permit the production of ultrapure metals and crystals. New types of glasses could be produced by cooling molten oxides into the glassy state without external disturbances that nucleate unwanted crystalline grain growth. Semiconductor crystals might be shaped directly from the melt into forms ready for use.

The lack of buoyancy should allow us to maintain a very homogeneous mixture of substances of varying density. This would prove highly beneficial in the production of such products as foamed metals, metal composites, and electrophoretic separation of large organic molecules in buffer solutions.

The most sophisticated source of control over space processes lies in the fact that heat and mass transport in liquids and gases will be predictable and controllable when the complicating influence of convection is suppressed. This has particular application in growth of large single crystals of high purity. It should also prove useful in the development of unique and useful new structures in two-phase alloys, such as eutectic and monotectic systems and in making specialized optical components free from defects that limit their performance.

These are only a few examples thought of in the earliest stages of the program without any data from actual space experiments. Considerably more research is needed to ascertain the real potential of these new possibilities. Furthermore, as we continue our studies, many new ideas will become apparent that should be pursued.

Our current research effort has a twofold purpose, as shown in Figure 5. The major portion of our study activity is aimed toward expanding our understanding of the potential to be derived from space processes in these promising areas of materials processing. The studies also point up the requirements and capabilities that must be provided by our experimental facilities in space. Based on these requirements, a second element of our study activity is directed toward evolving apparatus technology and experimental techniques needed for development of an experiment facility in space which can support large numbers of experiments with varying needs. A few studies also have been undertaken to better establish user interest and examine the economic potential of some of the more promising processes.

Looking ahead, I would expect our support of the basic technology effort to begin leveling off. However, as new ideas develop, work in these new areas will be emphasized. If we look at Figure 5, we see that most of our technology effort to date has been directed toward crystal growth and metallurgy. As our base of interest is broadened, new concepts and ideas should be identified with need support.

The second immediate goal of the program is to broaden our base of interest both internally and externally. The expertise and support of other NASA centers is needed to develop the full potential of materials processing and manufacturing in space. Similarly, the involvement of outside organizations needs to be expanded.

Expanded User Involvement

Referring to Figure 5, we find that approximately 20 organizations are actively involved in the Materials Science and Manufacturing in Space program. Furthermore, while it is not readily apparent from Figure 5, the majority of these groups are aerospace or space-related organizations. A much broader base of involvement is needed, particularly from the nonaerospace research and industrial community, and some preliminary surveys indicate that interest exists among these potential users.

Following the Space Station Utilization Conference, held last year at the Ames Research Center, some 20 nonaerospace research, development and manufacturing organizations completed questionnaires expressing interest in this applications area. A similar survey of European companies and research labs in eight countries drew 76 responses of positive interest in the Materials Science and Manufacturing in Space program. These results are highly encouraging.

A number of measures are being pursued to capitalize on this interest (Fig. 6). The program plans to create more user awareness and provide more avenues for user participation through:

1. Increased contact with the user community to determine their needs and acquaint them with the possibilities of space research to solve their problems.

2. More possibilities for user participation through open procurement, thereby stimulating a diversity of ideas through the competitive process.

3. Increased opportunities for companies to conduct space research by taking maximum advantage of flight opportunities of current and planned flight programs. This will be discussed in more detail later in the paper.

4. Persistent missionary work at technical symposia, laboratory colloquia, technical society meetings, etc., to acquaint the user community of the available possibilities for space research in materials processes.

5. Development of a fair and workable approach to the commercial users of space that avoids unwarranted advantages and yet offers commercial incentives by protection of proprietary rights. Although no formal policy has been established as yet, our objective is to encourage private utilization of our space capability. To this end, we would adopt a policy as liberal as possible and consistent with public interest in accommodating industrial involvement. Specific arrangements will be worked out on a case-by-case basis.

Flight Opportunities

So far we have discussed only the ground-based activities which support the Materials Science and Manufacturing in Space program. However, by its nature, this program requires the space environment to exploit the effects of null gravity on materials processes and product characteristics. Furthermore, the kind of special attention and close control required to conduct the kind of experimentation planned in space makes the program best suited for manned space missions. Consequently, the experiment program is being developed for manned flight.

The Apollo program offers the only manned space flight possibilities for the next few years. Since the primary objective of Apollo is lunar exploration, it affords very little opportunity for other areas of experimentation. However, Apollo missions do sometimes have enough residual resources to accommodate small, self-contained experiment packages intended for operation on a noninterference basis, making use of residual mission resources during the earth-moon drift phase. Several simple demonstrations of techniques and concepts of basic importance to design of later experiments have been developed to take advantage of this capability. They include (Fig. 7) a sensitive test for any convection effects that may exist at very low force levels, a feasibility test of electrophoretic separation in a liquid medium and a study of composite casting, and crystal growth metals solidification of low temperature materials in null gravity. These demonstrations were initially conducted on Apollo XIV with varied success, and reports on the results will become available in the near future. Improved versions of these demonstrations, building on Apollo XIV experience, are now under development for flight, hopefully on Apollo XVI and/or XVII.

A more ambitious experiment program is being implemented for the Skylab program scheduled for 1973. During the development of experiments for the Skylab, it became evident that experiments for manned missions can be built more cheaply and easily if they can be performed in an existing general-purpose facility. Therefore, a specialized facility is being developed for Skylab with the versatility to accommodate a variety of materials science investigations selected for flight. This facility contains a spherical vacuum chamber to house the experiments, an electron beam unit for sample heating, and a control panel to control experiment activities. Other services, such as water, spacecraft power and motion picture coverage, are also available.

Five experiments related to the program are currently approved for flight on Skylab (Fig. 8). They consist of metallurgical experiments to study the effects of reduced gravity on solidification, grain structure and mechanical properties of metals and composites, and the growth of a single gallium arsenide crystal by solution transport.

Although this experiment program on Skylab is quite limited, it does provide an early opportunity to gain experience in the development and integration of individual experiments into a common facility. This experience is particularly valuable as we plan our experiment program for the Shuttle.

With relatively simple modifications to the M512 facility, the experiment complement of the Materials Science program on Skylab could be significantly expanded. Two modifications which are being considered include the addition of a multipurpose electric furnace and an electromagentic positioning system for levitating samples. With these additions, a large number of samples of alloys, composites, and crystalline materials could be accommodated from the industrial community for minimum cost and complexity.

Another possibility includes the addition of a carry-on-type electrophoretic separator, designed to be reloadable in flight. Hence a large number of biological samples could be carried to orbit, separated, collected, and returned to earth for analysis.

Even though these possibilities look attractive, it must be remembered that changes to Skylab hardware at this late date are very difficult, and the feasibility of these modifications is quite uncertain. However, there are several other potential mission prospects in the interval between Skylab and the Shuttle. These include a possible second Skylab mission and/or one or more Command and Service Module (CSM) flights. Planning in the material science area to take advantage of these possibilities is underway including incorporation of the modified M512 facility described above.

Although we expect useful results from our Apollo and Skylab missions, our first opportunity for research and development work, on the scale needed to generate ultimate applications, will come with the Space Shuttle. For the Space Shuttle missions NASA plans to provide a relatively large inventory of modular, general-purpose lab equipment that can be configured flexibly to match experiment requirements and spacecraft resources on any mission where space is available. One concept for a Materials Science and Manufacturing in Space Laboratory to be used with the Shuttle is shown on Figure 9. As envisioned in this concept the equipment would include a "core" instrumentation and control rack to provide general support on any mission. Special-purpose modules could then be added to meet the particular experiment requirements of a mission. These special-purpose modules would include vacuum chambers, furnaces, levitation apparatus, biological processing equipment, fluid-handling facilities, etc. Each of these major components would be backed up by an inventory of subassemblies that could be flown repeatedly in many different combinations as experiment requirements dictate. By reuse of this basic equipment, program cost can be substantially reduced.

Through this approach we hope to simplify interfaces between the experiment and spacecraft, and reduce cost and lead time for experiment development. Experiments generally will only be called upon to supply samples and instructions for processing them in NASA's payload apparatus. Thus large numbers of users can be accommodated at modest cost and a minimum lead time — on the order of weeks to months from acceptance to flight, instead of 3 to 5 years required in current programs.

Long-Range Program Prospects

During the early period of Shuttle operation, experimentation would be limited to short-duration missions (7 to 30 days), carried out within a module which remains attached to the Shuttle. In this period, the program emphasis will be on research experiments which provide information useful to our ground technology, as well as those that build up our understanding of processes in weightless media, which eventually may provide an economic payoff.

When permanently orbiting space stations begin to be available, research will continue, using apparatus that will have evolved from the Shuttle payload inventory, but development work will also begin on a few of the processes that seem most promising at the time. It is hoped that some of these processes will be ready for pilot-scale manufacturing operations as soon as the Space Station complex can support this level of activity, and that a few of them will reach full-scale commercial manufacturing status in the latter part of this century. By the turn of the century, space manufacturing may account for a significant fraction of all space operations, and thereafter it is likely to play a large role in assuring a permanent future for space flight because of the essential functions it will perform in some parts of the world's economic activity.

- AN APPLICATIONS PROGRAM THAT SEEKS TO DELIVER CONCRETE ECONOMIC BENEFITS FROM MANNED SPACE FLIGHT:
  - INDIRECT BENEFITS FROM RESEARCH RESULTS THAT EXPAND KNOWLEDGE OF MATERIALS
  - DIRECT BENEFITS FROM CREATION OF NEW PRODUCTS OR IMPROVEMENTS TO EXISTING ONES

Figure 1. Materials science and manufacturing in space.

- BUILD-UP OF THE TECHNOLOGY BASE
  - PROCESS R & D
  - ENGINEERING DEVELOPMENT
- EXPANDED USER INVOLVEMENT
- MAXIMUM UTILIZATION OF EXISTING FLIGHT OPPORTUNITIES

Figure 2. Immediate program goals.

TYPE OF ORGANIZATION	ACTIVELY SUPPORTED	SUPPORT SOLICITED
AERO SPACE AND DEFENSE	5	4
R&D COMPANIES	1	4
UNIVERSITIES	5	
COMMERCIAL ORGANIZATIONS	4	1
OTHER GOVERNMENT AGENCIES	2	

Figure 3. Organizations involved.

- CRYSTAL GROWTH
  - CRYSTAL GROWTH FROM CONVECTIONLESS SOLUTIONS & VAPORS
  - CRYSTAL GROWTH FROM MELT, SHAPED FOR FINAL USE
  - FLOATING ZONE REFINING
- METALLURGICAL PROCESSES
  - METAL MATRIX COMPOSITES
  - EUTECTIC & MONOTECTIC ALLOYS OF CONTROLLED STRUCTURES
  - FOAM CASTING
- BIOLOGICAL PREPARATIONS
  - ELECTROPHORETIC PURIFICATION OF VACCINES
  - INCUBATION PROCESSES FOR BIOLOGICALS
- GLASS PREPARATION & PROCESSING GLASSES
  - PRODUCED BY CONTAINERLESS SOLIDIFICATION
  - HI QUALITY LENSES FOR LASERS & OPTICAL INSTRUMENTS
- PHYSICAL PROCESSES IN FLUIDS
- CHEMICAL PROCESSES IN FLUIDS

Figure 4. Technical areas for potential exploitation.

PROCESS R & D	CONTRACT		IN-HOUSE	
	FY-71	FY-72	FY-71	FY-72
CRYSTAL GROWTH	5	7	2	2
METALLURGICAL PROCESSES	4	6		
BIOLOGICAL PREPARATIONS	2	3		
GLASS PROCESSING	1	1		
PHYSICAL PROCESSES IN FLUIDS	1	2		
CHEMICAL PROCESSES IN FLUIDS			1	1
ENGINEERING DEVELOPMENT				
FACILITIES DEFINITION	3	6	2	2
LABORATORY CONCEPTS		1		
USER INTEREST	2			

Figure 5. Current program structure.

- DIRECT NASA/USER CONTACT
- OPEN COMPETITION FOR CONTRACT WORK
- MAXIMIZE OPPORTUNITIES FOR FLIGHT RESEARCH
- SYMPOSIA & TECHNICAL MEETINGS
- PROTECTION OF USER INTEREST

Figure 6. Expansion of user involvement.

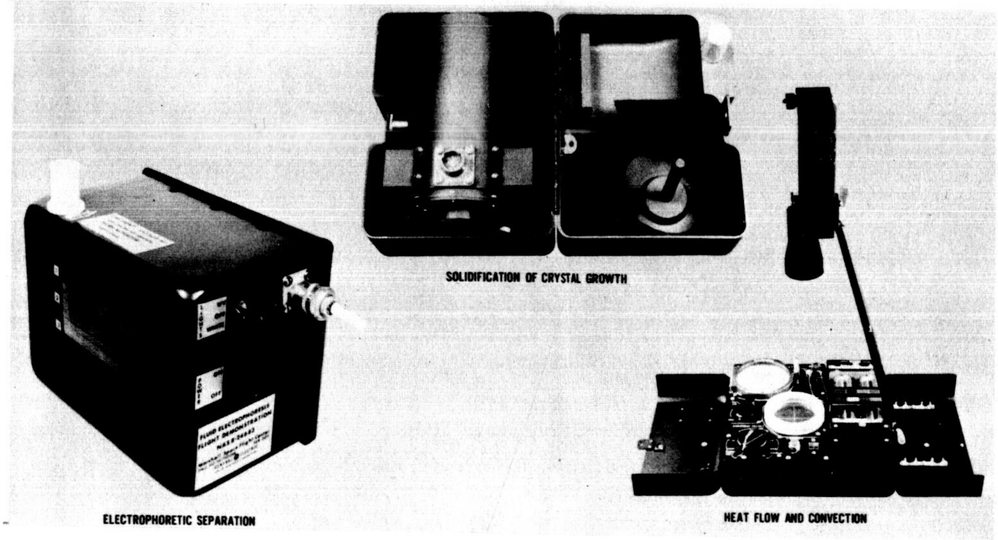

Figure 7. Apollo demonstrations.

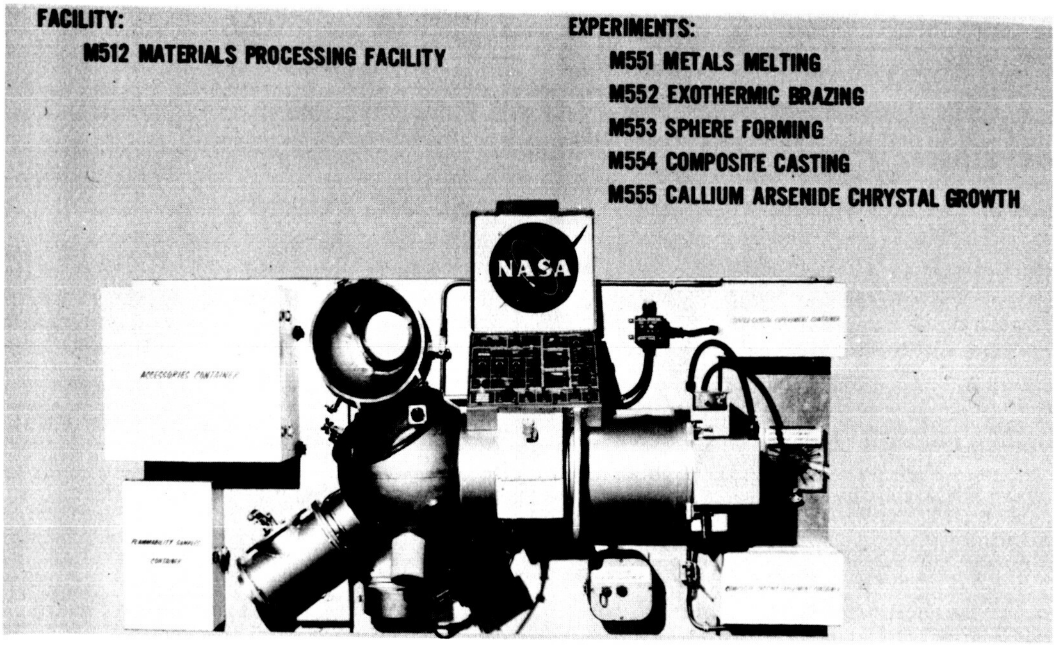

Figure 8. Skylab apparatus.

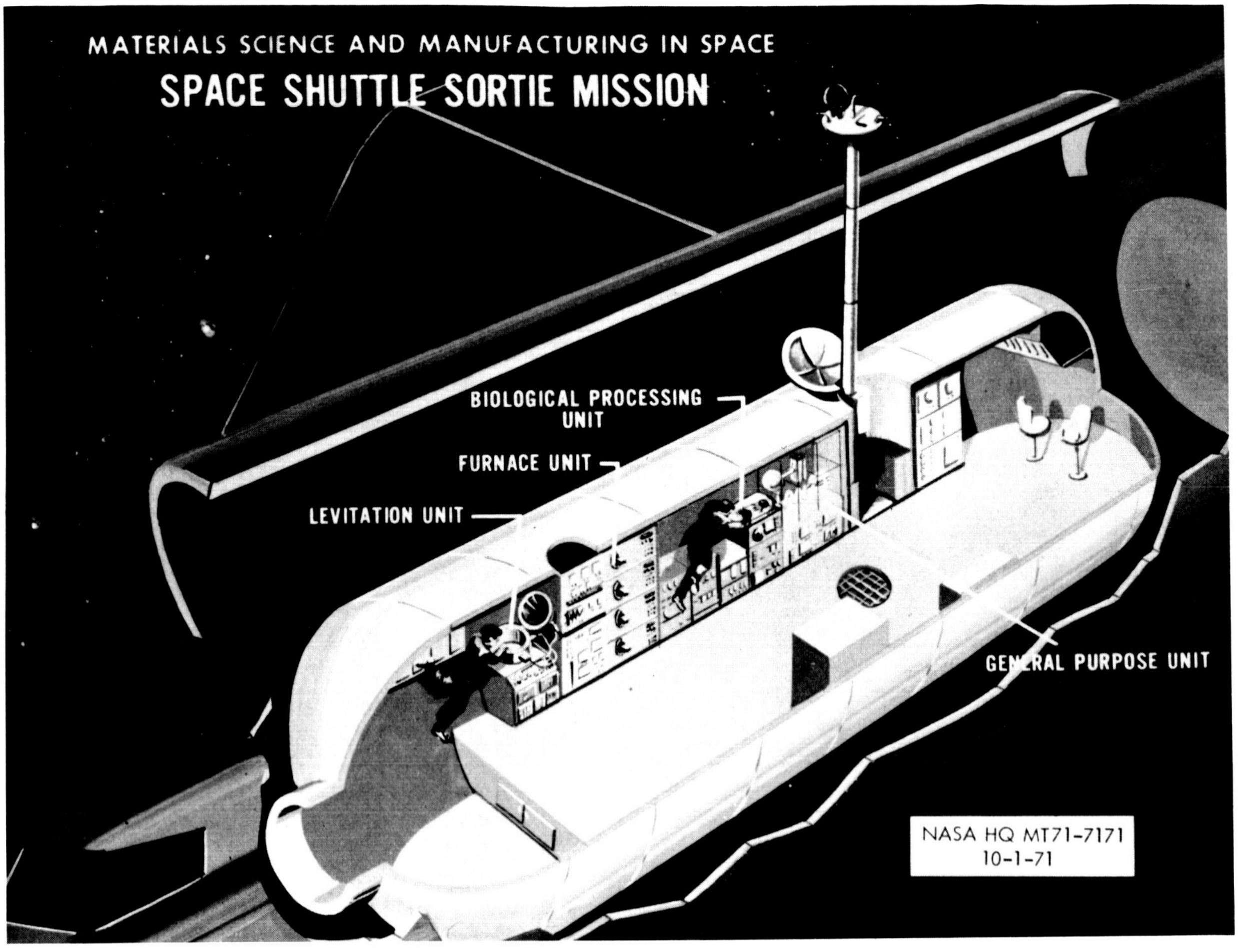

Figure 9. One concept for a Materials Science and Manufacturing in Space Laboratory.