Appendix D

MATERIALS SCIENCE AND ENGINEERING IN MICROGRAVITY*

Introduction

Two hundred miles above Earth, unfiltered solar radiation, a near-perfect vacuum, and temperature extremes ranging from –200° to +200° F exist in an environment almost free of gravitational force. The recent interest in materials processing in space (MPS) has its origin in the belief that the unique attributes of this environment may have important scientific and commercial applications.

With the exception of microgravity, the attributes of the space environment can be duplicated on Earth in sufficient quantities and duration to investigate their extended effect on processes and materials. Though microgravity can be simulated by using airplanes, sounding rockets, and in some instances magnetic fields, such simulations are generally of short duration, involve only limited quantities of test material, and often introduce complicating factors such as vibration and impurities. The long-term microgravity environment of space introduces a new dimension in controlling process variables such as temperature, composition, and fluid flow. Through this experimentation, new opportunities for understanding and improving ground-based production methods will be created, and, where practical and economical, select materials may be produced in space.

Scientific Status of Materials Processing in Space

Microgravity Alterations of Processing Phenomena

By using the long-duration, microgravity environment of an orbiting spacecraft, new manufacturing processes can be designed. On Earth the theoretical performance characteristics of materials are inhibited by such gravity-induced phenomena as convection, segregation, buoyancy, and sedimentation. These phenomena function in the following manner:[1]

Convection. The spontaneous stirring and mixing that occurs as currents flow between temperature gradients in a liquid or gas are unpredictable and chaotic, and can lead to unwanted structural and compositional differences in solid material. Both crystal growth and solidification processes are enhanced if convective disturbances are suppressed. The microgravity of space should provide a means to suppress convective phenomena.

Sedimentation/Buoyancy. On Earth, gravity causes heavier components to settle in a mixture while less-dense materials rise. Sedimentation and buoyancy complicate manufacturing techniques for alloys of different density elements and for composite materials. In microgravity, lighter density materials will remain in suspension for indefinite periods of time, thereby allowing the processing of homogeneous composites and alloys where the constituents have large density differences.

Hydrostatic Pressure. Hydrostatic pressure puts a strain on materials during solidification. Certain crystals are sufficiently dense and delicate that they are susceptible to strain under their own weight at growth temperatures. Such strain-induced deformations in crystals degrade their electro-optical performance. In microgravity, heat-treated, melted, or resolidified alloys might be developed free of deformation by coating the machined shape with a thin oxide skin, serving as a mold.

Container Effects. Containerless processing eliminates problems of container contamination and wall effects, often the greatest source of impurities and imperfections while forming molten material. In microgravity, a material may be melted, manipulated, and shaped, free of contact with a container or crucible by using acoustic, electromagnetic, or electrostatic fields. Surface tension would hold the material together in mass, a force overpowered hereon Earth by gravity.

MPS Product Applications

In general, the MPS program is interested in studies of process parameters to enhance control and productivity in Earth manufacturing, to prepare limited quantities of precursor materials to provide baseline or reference data, and to develop methods unique to the space environment by which materials can be prepared. All these research tasks rely upon the range of process parameters being extended through the reduction of gravity.

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*McDonnell Douglas, the Materials Processing in Space Projects Office of NASA, and TRW each provided a case study for this appendix. Their aid is gratefully acknowledged.

[1] See generally: L. K. Zoner, "Materials Science and Engineering in Space," in *Commercial Operations in Space, 1980-2000*, 18th Goddard Symposium, AAS, vol. 51, Science and Technology Series, 1981, pp. 20-26; K. Moritz, "In the Realm of Zero-G," *TRW Systems and Energy*, winter 1978, pp. 16-24.

Examples of potential applications derived from MPS research are as follows.

Crystal **Growth**[2]

Melt growth is the most widely exploited technique to produce high-technology, single-crystal materials for semiconductor chips used in large-scale integrated circuits for communications and computers. Chemical homogeneity, which will maximize electrical performance, is believed possible through microgravity processing. Commercially valuable crystals for sensitive infrared sensors, most difficult to grow on **Earth, may be enhanced by melt growth in a microgravity** environment.

As a variation of melt growth, float-zone growth techniques are widely used to produce crystals such as doped silicon for semiconductors and solar cells. Although large, efficient crystals are grown commercially with this process on Earth, gravity does limit the size and type of crystals that can be produced and introduces growth rate fluctuations that cause chemical inhomogeneities that necessitate cutting the crystal into small chips for high-performance applications.

Solution growth of crystals in the MPS program emphasizes creation of room-temperature, infrared detector materials, and gallium-arsenide (GaAs) semi-conductors for a wide range of applications from microwave devices to computers and solid-state lasers. Infrared defectivity of current available material is constrained to about 20 percent of the theoretical limit because of gravity-influenced growth defects. GaAs semiconductors can be readily grown on Earth, but with considerable imperfections,

The absence of gravity opens new possibilities for the growth of large, flat, pure crystals by vapor technique; therefore, the MPS program includes the investigation of $Hg1^2$ nuclear detector crystals that can be used at ambient temperature. Because the crystal has a layered structure, self-deformation during growth in sizes under 1 g is believed to be an important factor i n producing dislocations that degrade the performance of the crystal as a nuclear-energy detector. The growth of such a crystal in microgravity could eliminate such strains at the growth temperature.

Solidification3

Control of the solidification of metals and alloys is the key element in the field of metallurgy. Gravitational effects, such as buoyancy-driven convection of the melt or sedimentation, can greatly influence the structure of metals and alloys. Directional solidification in microgravity allows complicated shapes, such as turbine blades, to be melted and directionally resolidified to increase axial strength while using a thin oxide skin to maintain the shape. Additional interest is based on the potential of approaching the theoretical maximum magnetic strength of materials that are 10 times higher than currently realized on Earth.

Another group of potential candidates for in-space production is that of miscibility gap alloys. These alloys defy preparation on Earth in bulk quantities because of gravity-driven effects that cause the materials to segregate upon solidification. There are some 500 such combinations of materials that have a liquid-phase miscibility gap. Processed in microgravity, these materials might have such diverse applications as electrical contacts (as replacements for silver and gold) and self-lubricating bearings.

Solidification kinetics in the casting of alloys under nonterrestrial conditions can produce fine-grained structure in the interior of a casting. This phenomenon could have application in common products such as iron engine castings.

Undercooked solidification is the rapid quenching of molten materials at temperatures well below their freezing points. By containedess processing in microgravity, a vast array of materials is expected to be processed in the amorphous state, thus extending the materials properties available to mechanical and optical designers. Enhanced glasses manufactured by means of this process could improve their energy-transfer efficiency for applications such as laser hosts. In addition, such studies may shed light on methods for obtaining superconductors that work at higher temperatures.

Containerless Processing

Containerless processing may permit the creation of amorphous (glass) materials that cannot be made on Earth, and may allow the analysis of molten materials at temperatures that would exceed the melting point of crucibles on Earth. By elimination of nucleation associated with container walls, it should be possible to extend the glass-forming range of many materials, including some metals, resulting in new and unique glasses with exotic properties. An application of this process is in the production of ultrapure glass used in optical waveguides for high-frequency communications. Other possible applications are fusion-**energy lasers, fiber optics communications, cable networks, and self-focusing lenses.**

[2]S. Waters, "Tapping the Resources of a New Continent, " Part 1—Materials Processing, *Mechanical Engineering,* June 1981, pp. 26-39.

[3]S. Solomon, "Factories in Space," *Science Digest Special,* September/October 1980, pp. 58-61, 114,

[4]N. J. Barter, "Materials Processing in Space, " Impact for the 1980's–Conference on *Selected Technology for Business and Industry,* May 14-15, 1980, pp. 11-16,

Fluids and Chemical Processes[5]

On **Earth, fluid and chemical processes are affected by gravity-driven convection or sedimentation. Microgravity eliminates these effects, thereby allowing components to be isolated for study with a** degree of freedom not otherwise possible.

A potential application of this technique would be the production of monodisperse latex spheres in space. These spheres are too large to be grown by polymerization and too small to be sized by microsieving on Earth. Because of the absence of sedimentation in microgravity, these latex spheres might be mass produced from a polymerization process while in suspension. These spheres, available only in research quantities, are used in calibrating electron microscopes, light-scattering devices and filters, in the measurement of pore size in membranes, and in serological tests for a multitude of diseases.

The biomedical applications of microgravity such as electrophoresis, isoelectric focusing, phase partitioning, suspension cell culturing, crystallization of macromolecules, and blood flow (rheology) processes will also be evaluated in the MPS program. Application of these techniques in biomedical sciences could lead to production of human insulin; purification of hemopoietic stem cells for treatment of certain types of leukemia; or production of collagen, used for artificial corneas, artificial skin for wound and burn treatments, and for membranes to aid i n cardiovascular and orthopedic surgery.

Status of MPS Technology

History of the MPS Program

The space processing program presently sponsored by the National Aeronautics and Space Administration (NASA) germinated in the mid-to-late 1960's,6 fostered by the need to master propellant characteristics, fire control, and the assembly of structures in space–elements all essential to manned spaceflight. Propellant requirements of the Apollo lunar landing program stimulated research on the effects of surface tensions and inertia in partially filled containers. Similarly, interest in on-orbit repair and assembly required engineering studies of brazing and welding phenomena under microgravity conditions.

In the course of these investigations, it was found that unrestrained liquid masses would form large free-flying globules, that vapor bubbles could grow virtually without limit in boiling liquids, and that flames quickly become blanketed with their own combustion products. These effects of weightlessness were first treated as problems in the engineering of spacecraft systems, only later to be recognized as exploitable phenomena useful in creating novel processes and products in space.

In 1966, personnel from NASA's Marshall Space Flight Center embarked on a series of visits to manufacturing companies to explore possible industrial interest in space applications. In 1969, NASA initiated its first formal space processing activities under the program title: "Materials Science and Manufacturing in Space." This program was jointly sponsored by the agency's Office of Manned Spaceflight and Office of Aeronautics and Space Technology. To date, in-space MPS research has been pursued on the Apollo, Skylab, and Apollo/Soyuz manned spaceflight programs.

Apollo[7]

An MPS flight experiment program was inaugurated in 1971 when three "demonstration" experiments were performed on the Apollo 14 lunar mission. These simple science demonstrations consisted of heat flow and convection, electrophoretic separation, and composite casting experiments. On Apollo 16 in early 1972, a more ambitious electrophoresis experiment was conducted, and in 1972 Apollo 17 carried a heat-flow and convection demonstration.

Skylab[8]

The 100-ton Skylab space laboratory station, flown 1973-74, offered the first opportunity for extensive experimentation in the microgravity environment of space. A total of 15 MPS experiments and nine science demonstrations were conducted on Skylab. The complement of MPS experiments included: crystal growth, metal composites, eutectics (a combination of two materials that has a lower melting point than either material alone), welding and brazing, fluid effects, and combustion processes.

A materials processing facility (MPF) was an integral part of Skylab and was designed to accommodate all

[5]N. J. Barter and D. M. Waltz, *Materials Processing in Space: A Weightless Proposition,* AIAA-80-0878, presented at AIAA International Annual Meeting and Technical Display, Baltimore, Md., May 6-11, 1980, pp. 3-4; E. C. McKannan, *Survey of U.S. Materials Processing and Manufacturing in Space Programs,* NASA TM-82427, George C. Marshall Space Flight Center, Alabama, July 1981, p. 1.

[6]J. H. Bredt, "Status of NASA Space-Processing Research," in *Processing and Manufacturing in* Space, proceedings of a symposium held at Frascati, Italy, by European Space Research Organization, Mar, 25-27, 1974., p. 76; Op. Cit., L.K. Zoner, 1981, pp. 19-20.

[7]J. H. Bredt, op. cit., 1974, p. 77.

[8]*Skylab, Our First Space Station,* Leland F. Belew (cd.), NASA SP-400, Washington, D.C. 1977, pp. 148-1 51; *Skylab Experiments, Materials Science, Vol. 3,* NASA EP-1 12, May 1973; *Proceedings of Third Space Processing Symposium—Skylab Results, vol.* 1 and 2, Alabama, June 1974.

Skylab space processing experiments involving the melting and resolidification of materials. This facility was capable of venting into space, thus providing an evacuated environment for the experiments desired. A multipurpose electric furnace, capable of reaching 1,000° C, was fitted within MPF allowing eight metals experiments to be conducted.

Apollo/Soyuz[9]

The joint Soviet-American Apollo/Soyuz Test Project (ASTP), which flew in 1975, carried 12 space processing experiments and three demonstrations. Among them: crystal growth of semiconductors, zero-gravity processing of magnets, surface tension-induced convection, density separation during solidification of two alloys, and halide eutectic growth, In addition, two electrophoresis experiments were conducted on ASTP, one of which was developed and funded by the Federal Republic of Germany.

A modified Skylab furnace, capable of reaching 1,150°C with increased control of temperature ranges, was carried aboard the ASTP. ASTP allowed several investigators to confirm Skylab results and make additional tests of previously observed phenomena.

The Apollo, Skylab, and ASTP experiments were conceptually simple and limited in scope. The hardware was designed on the basis of equipment used on the ground and the experiments were supported by limited Earth-based research. Consequently, the experiments were basically reproductions of current techniques of processing materials carried out under low gravity conditions. With the close of the Apollo program in 1975, no further MPS spaceflight opportunities were available.

The STAMPS Report

A special study to provide guidance for NASA's program for materials processing space was published in 1978 by the Committee on Scientific and Technological Aspects of Materials Processing in Space (STAMPS),[10] an ad hoc committee of the Space Applications Board under the National Academy of Sciences (NAS). Drawing on comments and advice from more than 100 experts in materials science and technology, the NAS study concluded that the prospects for economical space manufacturing are limited and need to be better defined on a case-by-case basis. Further, the STAMPS report stated that no examples of economically justifiable processes for producing materials in space could be found.

The STAMPS committee stressed two points that emerged from the testimony of its advisors and from previous materials experimentation in space:[11]

> First, the space environment usually contributes at least as many problems as it solves. In sophistication, reliability, convenience, and cost, terrestrial experimentation is generally superior to what can be expected in space. Second, space experimentation will have little value unless its planning is founded on substantial Earth-based information and unless the results are coupled to those of complementary terrestrial programs. "

The STAMPS report indicated that some space environment parameters, such as the level of vacuum, temperature, or high-energy radiation can be better realized on Earth. Even long periods of low gravity, achieved only through orbital flight, may be jeopardized by several factors. Among these are: gas venting, fluid dumps, use of evaporators, crew motions, and perturbations of the shuttle orbit itself. These factors could induce accelerations, creating small forces of gravity (G-jitter), which in turn might affect the low-gravity requirement of space processing.

Singled out in the report were commercial space processing of vaccines using electrophoresis (the separation of particles of different mass/charge ratios in an electric field) and growing silicon crystals for use in electronics. The STAMPS study found no clearcut advantage in either case over terrestrial processes, In the case of electrophoresis, use of the technique on Earth has not yet been optimized.

The study group commented that low gravity appears to offer certain capabilities in studying the properties of boiling, combustion and melting, processes that are not now well understood. It was also felt that the ability of containerless processing to avoid contamination and increase purity may hold great promise. But even these possibilities must be subject to critical evaluation of comparative costs and likelihood of success. The NAS study group indicated that the commercial utilization of such understanding lacks promise.

The STAMPS committee suggested that the organization and management of future space processing should include the use of the space shuttle as a national facility. This would include use of the Spacelab by scientists and engineers working in universities, government laboratories, or industrial concerns. User rates should be established, but not designed to cover the total real cost of operating the facility.

[9] *Apollo-Soyuz Pamphlet No, 8: Zero-G Technology,* NASA EP-140, Washington, D.C. October 1977.

[10] *Materials Processing in Space,* report of the Committee on Scientific and Technological Aspects of Materials Processing Space, National Academy of Sciences, Washington, D. C,. 1978.

[11] Ibid.

In concluding its findings, the STAMPS study suggested the demonstration and development of significant materials processing in space techniques should be paid for by NASA. To this end, the committee suggested certain technical and management changes to improve the effectiveness of the NASA MPS effort. The STAMPS report noted that NASA's MPS efforts had "suffered from poorly conceived and designed experiments, often done in crude apparatus, from which weak conclusions were drawn and, in some cases, overpublicized."

In consonance with the recommendations of the STAMPS committee, a scientific advisory committee has been formed, responsive to the MPS Division Director, to aid in future program planning and policymaking relative to scientific aspects of the program. Peer groups have been empaneled to assist in the selection and periodic review of scientific experimentation and the periodic review of plans and policies.[12]

Terrestrial Facilities

In the absence of spaceflight opportunities for MPS experiment, NASA began using drop tubes and drop towers, aircraft, and sounding rockets to simulate the microgravity environmental J Using such ground-based research technologies, prospective MPS investigators could acquire microgravity test data to: 1) establish experiment parameters, 2) establish proof of concept, and 3) provide specimens for laboratory research.

Drop tubes and towers

To provide a low-cost, flexible and readily available low-g test facility, the Marshall Space Flight Center operates two drop tubes (one of 100-ft length and one of 300-ft length). These drop tubes provide 2 to 4 seconds of microgravity.

In drop tubes, molten droplets are released into a column of vacuum and are solidified during 2.6 seconds of vertical free fall, thus experiencing an effective force of 10-7 g. Typical experiments utilizing this facility include studies in high-temperature calorimetry, and in liquid densities, surface tensions, and volume changes due to solidification,

In using the drop tower, an experiment package is placed in a canister thrusted by small rocket motors to overcome air resistance and guide-rail friction. Experiment-laden canisters as heavy as 204 kg can experience an effective force of as little as 10^{-5} g during a 4-second drop tower test. Drop towers proved invaluable in verifying apparatus and experimental concepts flown on Skylab. Typical experiments are similar to those performed in a drop tube.

Research aircraft

NASA employs KC-1 35 and F-1046 aircraft, flying on parabolic trajectories, to provide 10 to 60 seconds of microgravity. Experiment packages flown in the KC-1 35, because of the size of the aircraft, can be larger in size than in the small F-104B, although approximately twice the microgravity environment can be obtained (30 to 60 seconds) by the jet fighter. Minimum gravity level obtainable is approximately 10-2 g. However, this value is unsteady, and therefore these means are unsuitable for precise experiments. Although the data obtained from research aircraft are limited, such flights do allow for valuable crew training, experiment hardware development, and verification tests.

Sounding rockets

The space-processing application rocket (SPAR) program has been instituted to provide some continuity in flight experimentation between the ASTP flight and the space shuttle MPS opportunities.[14] The SPAR rocket is a Black Brant sounding rocket equipped with recoverable payload system. SPAR was introduced in 1975 and has accomplished nine flights to date. Typically, SPAR can attain between 4 to 7 minutes of low-gravity phenomena, providing levels of $1O^{-5}$ to 10^{-6}g for payloads up to 300 kg. Because of the severe launch environment as measured by acceleration, vibration and spin rate of SPAR at liftoff, and later spin down, MPS experiment design is an arduous undertaking. The short flight times of SPAR are not conducive to crystal growth or biological separation. However, they can be used for certain fluid and solidification experiments. The SPAR program has led to an inventory of low-cost hardware, suitable for longer duration experimentation during shuttle operation. A materials experiment assembly (MEA) designed to be compatible with the shuttle/Spacelab has been developed by using SPAR technology.

Shuttle/Spacelab Programs

An operational space shuttle will further the evolution of materials processing in space. MPS experimentation on planned shuttle flights of up to 1 month will make use of the following shuttle facilities:[15]

[12] E. C. McKannan, op. cit., July 1981, p. 18.

[13] Materials Processing in Space Program: Handbook for Participants, Prepared for NASA by ORI, Inc., February 1980, pp. III-5 to III-19.

[14] J. H. Bredt, "NASA Plans for Space Processing Experiments on Sounding Rockets," in *Processing and Manufacturing in Space,* proceedings of a symposium held at Frascati, Italy, Mar. 25-27, 1974, pp. 71-73; R. j. Naumann and H. W. Herring, op. cit., 1980, pp. 99-103.

[15] E.C. McKannan, op. cit., July 1981, P. 41.

Small Self-Contained Payloads

These containers are available for rent by companies, universities, and private citizens for a cost dependent upon the size and weight of the experiment package. Containers with a maximum weight of 200 lb and measuring 5 ft^3 can be rented for $10,000 (in 1975 dollars). They are accommodated on a space-available basis and must contain their own power and internal data recording systems. Though limited by size and the absence of in-space manipulation, the small self-contained payloads may provide data useful in larger Spacelab experimentation or in joint endeavors between industry and NASA.

Materials Experiment Assembly

The first article of new materials processing hardware to be flown i n the shuttle is the MEA, a self-contained package attached to a Spacelab pallet. MEA has been developed to be compatible with SPAR technology and reconditioned SPAR equipment. MEA operates under its own power, containing a control computer, heat rejection system, and data recorders, and can accommodate up to four experiments in its separately sealed subenclosures. It is anticipated that private institutions may wish to lease MEA from NASA to conduct experiments of a proprietary nature, although legal and financial aspects of this possibility have yet to be clarified.[16]

Spacelab Modules and Pallets

Shuttle MPS systems can be divided into two groups: 1) those located in the pressurized Spacelab module, and 2) those positioned on the Spacelab pallet. ' Spacelab is a habitable module providing a shirt-sleeve laboratory for scientists and engineers to work in space. Carried into orbit in the shuttle cargo bay, Spacelab remains attached to the orbiter for flight durations of up to 1 month. The interior of the module is fitted with racks arranged in single and double assemblies to house experiments.

Unpressurized, u-shapted segmented pallets can also be attached in the orbiter cargo bay. These pallets form an open porch, exposing instruments directly to space and accommodating experiments controlled from Spacelab, the orbiter flight deck, or the Earth. Up to five pallets can be fitted in the cargo bay and combinations of modocles and pallets can be flown.

The major "facility-class, multiuser instruments" presently under development in the shuttle/MPS program consist of:[18]

- *Fluid Experiment System (FES):* Mounted in a double rack aboard Spacelab, the FES experiment uses Schlieren photography and holography to study fluid behavior under microgravity.
- *Vapor Crystal Growth (VCG) System:* Crystals are to be grown from fluids, vapors, or from melts of solid materials, recorded by holographic and video recording in common use with the FES.
- *Acoustic Contain Containerless Positioning Module (ACPM):* The ACPM is located on a pallet and uses 3-axis acoustic positioning to control the position and rotation of a sample heated radiantly to temperatures up to 1,600° C.
- *Solidification Experiment System (SES):* A modular furnace facility "that can accommodate up to 16 samples per flight that are automatically loaded and unloaded on command. These samples can be processed with uniform heating and cooling or with a temperature gradient and directionally solidified. SES is to be located on a Spacelab pallet.

As funding permits, additional MPS/shuttle activity is expected to include the following systems:[19]

- *Floating Zone System:* Used to determine how far the zone refining technique can be carried in space, and to what degree crystal size and purity can be increased. Attached to a pallet.
- *Electromagnetic Containerless Processing System:* A processing module for heating and cooling control independent of positioning control. Attached to a pallet.
- *Bioseparation System:* Designed to enhance understanding of electrophoresis and its variations. Contained in Spacelab.
- *Electrostatic Contain Processing System:* Used for processing and shaping larger, complex materials. Contained in Spacelab.

Future MPS Efforts

Three types of materials processing experiments have been selected for future shuttle missions. These are:

Group 1. Experiments that take advantage of the greatly reduced convective flow to provide quiescent growth or solidification conditions with precise control of temperature, growth rate and composition. Experiments in this category include:

- growth of solid-solution single crystals;
- semiconductor materials growth in low-g environment;

[16] OP, cit note 17, pp. I II-52-III-53.

[17] J. R. Carruthers and L. K. Zoner, "Materials Processing Studies in Space, " NASA (unnumbered) Apr. 10, 1979, pp. 20-23.

[18] N. J. Barter and D, M. Waltz, op. cit., May 1980, PP. 4-5.

[19] D. Dooling, "The Space Factory" in the *Illustrated Encyclopedia of Space Technology*, pp. 21 9-220; R. J. Naumann, "U.S. National Report on Materials Processing in Space, " presentation to Working Group 8, Materials Science in Space, COSPAR meeting (No. 78-1 15), Innsbruck, Austria, June 1978, pp. 20-22.

- vapor growth of alloy-type semiconductor crystals;
- HgI_2 crystal growth for nuclear detectors;
- solution growth of crystals in zero gravity; and
- alined magnetic composites.

Group 2. Experiments involving glasses or glass processes. These experiments take advantage of the containerless aspects of space processing as well as the absence of Stokes bubble rise to investigate phenomena that cannot be unambiguously studied on Earth. Experiments in this category include:
- refining of glasses in space;
- physical phenomena in containerless glass processing; and
- containerless preparation of advanced optical glasses.

Group 3. The remaining experiments depend primarily on the absence of sedimentation to keep a material of different density in suspension during a process. Experiments in this category include:
- solid electrolytes containing dispersed particles;
- liquid miscibility gap materials; and
- production of large particle size monodisperse latexes in microgravity.

It is anticipated that the projected needs of MPS, as measured by numbers of samples, processing time, and power required to support sustained, systematic **MPS activity, will surpass present shuttle capabilities. Use of a 2S-kW power system has** been advocated to extend shuttle stay-time in orbit (from a maximum 30 days to 90 days) and to provide greater levels of power supportive of MPS payloads. Longer duration shuttle flights, coupled with increased power to conduct experiments, would reduce the net cost of experimentation.

Eventually, a materials experiment carrier (MEC) could serve as a transition between exploratory MPS research and prepilot manufacturing plants. MEC would carry several second-generation MPS modules and, attached to the 25-kW power system, would contain its own heat-rejection equipment, control and data systems. As a total unit, MEC and power system would fly freely, utilizing the shuttle only to deliver raw materials and to extract finished products for return to Earth,[20]

It is conceivable that the MEC activity will require increased human attention, necessitating habitable, Spacelab-type modules, which could lead to a manned space station. This station may well serve as a national space facility for large-scale, commercial space processing.[21]

Conclusions

The scientific basis for manufacturing commercial products in space is limited, resting on a total of 8 hours of in-space research. The economic rationale for fabricating materials in space, therefore, can be assessed only when a suitable reservoir of knowledge has been established. The result from sounding rockets, aircraft, and ground facilities as well as from the limited experimentation aboard spacecraft suggest, however, that space processing techniques which yield products of high value and low volume may be commercially feasible.

It must be recognized that even if a material is identified that is sufficiently unique, useful, and valuable to be manufactured or processed in space, the high inherent cost of space processing will be a strong incentive for industry to find means of duplicating the process on the ground or to find a cheaper substitute for the material. For this reason it may be desirable for the Government to subsidize the initial phases of MPS research and product development. The continued and orderly development of space-based manufacturing techniques will depend heavily upon the establishment of a firm national commitment to maintain and enhance U.S. space capabilities.

[20] R. J. Naumann and H. W. Herring, op. cit., 1980, pp. 107-108.

[21] D. M. Waltz and R. L. Hammel, "Space Factories, " (77-56), presented to the 28th International Astronautical Federation (IAF), Prague, Sept. 25-Oct. 1, 1977.