(NASA-TM-82427) SURVEY OF THE US MATERIALS PROCESSING AND MANUFACTURING IN SPACE PROGRAM (NASA) 71 p HC A04/MF A01 CSCL 22A

N81-27150

Unclas
G3/12 26909

NASA TECHNICAL MEMORANDUM

NASA TM-82427

SURVEY OF THE U. S. MATERIALS PROCESSING AND MANUFACTURING IN SPACE PROGRAM

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July 1981

NASA

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JULY 1981

SURVEY

of

THE U.S. MATERIALS PROCESSING

AND

MANUFACTURING IN SPACE PROGRAM

Prepared for

OFFICE OF TECHNOLOGY ASSESSMENT

OF THE CONGRESS

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ACRONYMS

AN	-	Applications Notice
AO	-	Announcements of Opportunity
AR&DA	-	Advanced Research and Development Activity
ASES	-	Advanced Solidification Experiment System
ASTP	-	Apollo-Soyuz Test Project
ATD	-	Authority to Proceed
BIO	-	Bioseparation
CFE	-	Continuous Flow Electrophoresis
EMC	-	Electromagnetic Containerless
ESC	-	Electrostatic Containerless
FES	-	Fluids Experiment System
FL	-	Float Zone
GCEL	-	Ground Control Experiment Laboratory
HGDS	-	High Gradient Directional Solidification
IGI	-	Industrial Guest Investigator
JEA	-	Joint Endeavor Agreement
JPL	-	Jet Propulsion Laboratory
JSC	-	Johnson Space Center
KSC	-	Kennedy Space Center
LaRC	-	Langley Research Center
LeRC	-	Lewis Research Center
MAUS	-	Materialwissenschaftliche Autonome Experimente Unter Schwerlosigkeit
MDAC	-	McDonnell Douglas Astronautics Company
MEA	-	Materials Experiment Assembly
MEC	-	Materials Experiment Carrier
MLR	-	Monodisperse Latex Reactor
MIT	-	Massachusetts Institute of Technology
MPS	-	Materials Processing in Space
MSFC	-	Marshall Space Flight Center
NBS	-	National Bureau of Standards
NSF	-	National Science Foundation
OSS	-	Office of Space Science
OSTA	-	Office of Space and Terrestrial Applications

ACRONYMS (Continued)

PI	-	Principal Investigator
P/L	-	Payload
PS	-	Power System
SES	-	Solidification Experiments System
SPAR	-	Space Processing Applications Rocket
SRT	-	Supporting Research and Technology
STAMPS	-	Scientific & Technological Aspects of Materials Processing in Space
STS	-	Space Transportation System
SWG	-	Science Working Group
TEA	-	Technical Exchange Agreement
TEXUS	-	Technologische Experimente Unter Schwerelosigkeit
VCG	-	Vapor Crystal Growth

SURVEY OF THE U.S. MATERIALS PROCESSING

AND

MANUFACTURING IN SPACE PROGRAM

I. INTRODUCTION

Objectives and Concepts of Materials Processing in Space (MPS)

MPS might better be described as materials science and engineering using low gravity. The primary motivation of the program is to use the unique environments of space for scientific and commercial applications. The elimination of the Earth's gravity during the production of common materials affords opportunities for understanding and improving ground-based methods or, where practical and economical, producing select materials in space. Large factories or mills producing huge quantities of materials, as is often the case on Earth, are not expected in space in the near future. Materials that might be produced in space, typically, would be of low-volume but high-value commercial interest. In the more distant future, extraterrestrial materials may be mined and processed for use in space applications.

To promote the potential commercial applications of low-g technology, the program is structured: (1) to analyze the scientific principles of gravitational effects on processes used in the production of common materials, (2) to apply the research toward the technology to control production processes (on Earth or in space, as appropriate), and (3) to establish the legal and managerial framework for commercial ventures.

II. PRESENT PROGRAM AND STRUCTURE FOR DEVELOPING MATERIALS PROCESSING AND MANUFACTURING TECHNOLOGY IN SPACE

A. Description of Present NASA Materials Science in Space

1. Federal Funded Research

The low-gravity, high-vacuum environment associated with orbiting space vehicles offers unique opportunities to investigate various processes in ways that cannot be duplicated on Earth. Gravity-driven convective stirring, sedimentation, and hydrostatic pressure are virtually eliminated. Materials can be melted, shaped, and solidified in the absence of a container. Processes that require an extremely high vacuum in conjunction with large heat loads or the generation of large quantities of gas may be performed in the wake of an orbiting vehicle.

The low-gravity environment offers a new dimension in process control. Since gravity-driven effects are no longer significant, diffusion-controlled conditions may be easily realized without resorting to the severe restrictions required in Earth's gravity. Many terrestrial processes can be improved or optimized by a better understanding of flows from which better control strategies can be devised.

The elimination of sedimentation in low gravity allows the study of a number of phenomena that cannot be adequately studied terrestrially. The absence of hydrostatic pressure eliminates the tendency for materials to sag and deform when melted and eliminates the need to contain liquids during processing.

Containerless processing eliminates problems such as container contamination and wall effects. Thermal processing and measurements can be done at temperatures well above the melting points of any known material or on materials that are extremely reactive in the melt. Containerless melting in the high vacuum, in the wake of an orbiting vehicle, could produce materials of unprecedented purity.

a. Crystal Growth - Of paramount importance in any crystal growth system is the control of the environment at the growth interface. Compositional and/or thermal fluctuations in the fluid phase (whether it be melt, solution, or vapor) can give rise to inhomogeneities or defects in the growing crystal. Since unstable thermal gradients are virtually impossible to avoid in any growth system, some convective stirring will almost always be present in convectional growth techniques. Such convective stirring is generally thought to be detrimental to the control of the growth process and is often considered to be the cause of many growth problems.

(1) Melt Growth - Crystal growth by solidification from the melt is the most widely used technique for production of high technology single-crystalline materials. The success of the technique depends on the control of the composition, temperature, and shape of the solidification interface. This control is often complicated by convection in the melt which affects both the heat and mass transport to the interface. This can cause compositional variations and growth fluctuations.

There is reason to believe, based on Skylab and Apollo-Soyuz experiments, that two major advantages can be realized by growing valuable single crystals in space, i.e., the ability to establish a steady-state, diffusion-controlled boundary layer at the growth interface, and the ability to eliminate growth-rate fluctuations Flight experiments are being developed to explore how a low-g environment might be used to overcome some of the difficulties in growing crystals. The solidifying surface is difficult to control on Earth and the growth is susceptible to breakdown.

(2) Solution Growth - One advantage of growth from a saturated solution, in which the solute is incorporated into the growing crystal inteface, is the control it provides over the temperature of growth. This makes it possible to grow cyrstals that are unstable at their melting points or that exist in several forms depending on their melting points or that exist in several forms depending on their temperature. A second advantage is the control of viscosity, thus permitting substances that tend to form glasses when cooled from their melt to be grown in crystalline form.

A number of interesting systems can be grown from transparent solutions at moderate temperature which allows the detailed study of the growth process and how it is related to growth environment. Because growth from solution requires transport of solute to the growth interface and removal of solvent, it is important to understand how the growth and perfection of the crystal are influenced by this transport process. Since the solvent virtually always has a different density from the solute, solute-driven convection is unavoidable in terrestrial processes. In fact, forced convection or stirring is generally employed in an attempt to maintain a uniform concentration of solution.

(3) Vapor Growth - Particular attention has been given in recent years to the growth of whiskers and to crystalline films from the vapor. Gravity-driven convection can play an important role in the transport of the vapor from the hot source to cold seed. Also, the growth environment in the vicinity of the seed can be influenced by convective effects. There will be both thermal and compositional changes arising from the heat of sublimination released as the vapor deposits. These effects together with natural convection arising from temperature gradients in the container can be expected to result in nonuniform growth conditions which would affect the perfection of the growing crystal.

Advantages that are expected from the study of vapor growth in space are: the avoidance of deformation of crystals that are weak at their growth temperature, the ability to grow films under unique vacuum conditions, and the possibility of containerless growth.

Several chemical vapor growth experiments were conducted on germanium-selenide (GeSe) and germanium-telluride (GeTe), using iodine (I_2) as the transport gas. The experiments were conducted at various pressures and in the presence of an inert gas in order to investigate the transport rates in low-g environment. In space, substantial improvement in crystalline structure was obtained in terms of fewer defects by visual inspection of micrographs. The most surprising result, however, was in the transport rates. Growth rates were substantially higher than expected, indicating that some unforeseen convective effect is operating in low-g or that some gravity-driven effect is lowering the diffusive transport in the ground-based experiment. In either case, it is apparent that such transport is not as well understood as we previously thought. Additional experiments are being planned to elucidate these transport processes and to explore the possible advantages of growing technically interesting systems such as HgCdTe by this process.

(4) Floating Zone Growth - Floating zone crystal growth is a variation of melt growth in which the melt does not contact a container. This is accomplished by supporting vertical polycrystalline rod at both ends and melting a portion of it with a suitable heater. This floating zone is supported along the sides solely by surface tension. By moving the heater or the rod, the hot zone can be made to move along the axis of the rod, melting the materilas ahead of it and growing a crystal bhenid it. Often the rod is rotated or the two portions are counter-rotated to even out any thermal variations.

The primary advantage of this technique is the absence of wall effects. Many materials of practical interest are highly corrosive in the melt and will partially dissolve any container. Because the electronic properties are dramatically affected by an extremely minute trace of impurity, uncontrolled wall contamination is a serious concern. Also the absence of wall-induced stress during the solidification process can lead to substantial improvement in crystalline perfection. For these reasons, float-zone growth is an extremely important process, especially for producing high-quality silicon and other electronic materials for applications in which high purity and perfection are required.

Floating zone growth is subjected not only to the control and stability problems at the interface that are encountered by ordinary melt growth but has also a new set of problems associated with the free surface. Because the hydrostatic pressure in the molten zone must be supported by surface tension, the length of the zone is limited by the material properties and the diameter of the system. Also the sagging of the melt under the hydrostatic pressure further complicates the control and, consequently, the size and shape of the growing crystal. Thermal convection in the melt is complicated by flows along the free surface of the melt.

It appears that float-zone crystal growth would benefit significantly from the low-g environment in space. The absence of hydrostatic head eliminates the deformation of sag in the molten zone. Zone lengths may be increased. Finally, the use of low-g processing extends floating-zone growth to materials whose low-surface tension prohibits this technique on Earth. One of the major problems in commercially-produced float-zone silicon is the lack of chemical homogeneity. Dopant striations and radial segregation produce considerable variations in electrical properties which can cause problems in very large scale integration devices or in large focal plane arrays. The use of more quiescent growth conditions in space should eliminate this problem.

b. Solidification of Metals and Alloys - Control of the solidification of metals and alloys is the key element in the vast field of metallurgy which provides us with the materials that are fundamental to our high technological society. Gravitational effects, such as buoyancy-driven convection of the melt or the sedimentation of various phases can greatly influence the structure of metals and alloys.

(1) Solidification Kinetics in the Casting of Alloys - In casting of alloys, the fluid, which has a different composition from the solidifying material, often becomes trapped in the spacings between the solid dendrites(tree-like structures extending into the melt). Dendrites break off as growth proceeds. They are carried by density differences or convective flows and either form new growth sites or migrate to the surface and produce mottled surfaces. This process is responsible for producing the fine-grained structure in the interior of a casting, as was recently shown by a series of ground-based experiments using a centrifuge and flight experiments using sounding rockets. This basic information may have application in common products such as iron engine castings.

(2) Unidirectional Solidification - Highly directional properties can be obtained with some castings by directional solidification. This technique affords a degree of control not available in normal castings in that a unidirectional thermal gradient can be imposed and the growth rate can be regulated by moving the sample relative to the thermal gradient. Convective effects can be diminished on the ground but cannot be completely eliminated.

Directional solidification is often used to produce natural composites with reinforcing structure in materials whose components have limited mutual solubility. The size and spacing of the microstructure are determined by the growth rate, the higher growth rates giving rise to finer microstructures. These higher growth rates require very high thermal gradients. Low-g offers several possible advantages. First, the reduced convection in the melt lowers the total heat transfer. Second, shapes can be maintained in low-g with a thin oxide skin, as was demonstrated in experiments performed on German sounding rockets. This 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. Without the heavy mold required on Earth to diffuse the heat, a very high thermal gradient can be imposed on the sample which can produce a unique structure.

It has generally been assumed that the microstructure of directionally solidified composites is controlled by diffusion. However, a recent experiment on a rocket flight obtained a finer, more regular microstructure in a maganese-bismuth/bismuth (Mn-Bi/Bi) composite sample than was obtained under identical processing conditions in Earth gravity. This indicates that residual convection may play a more significant role in such processes than was previously suspected.

Another advantage of low-g lies in the processing of off-normal compositions. By eliminating the convective stirring associated with one-g processing, it is possible to build up a layer of the rejected component until the normal composition is reached at the solidifying interface. To provide mass balance, however, it is necessary at steady state to incorporate the same composition into the solid as is present in the bulk melt. This results in both matrix and intrusive material solidifying but in proportions determined by the bulk melt composites. Low gravity provides a new degree of freedom in controlling the size, shape, and spacing of the two phases.

(3) Miscibility Gap Alloys - Hundreds of alloys have been identified which might have useful properties if they could only be processed, but the metals forming the alloys are not miscible on Earth; i.e., they will separate into two liquids at the melt temperature. These alloys are another important class of materials that require reduced gravity for detailed study. Attempts to form alloys or fine dispersions of such material in Earth's gravity by normal freezing are doomed to fail because of this incompatibility. As the melt temperature is lowered into the two-phased region, the low-temperature phase forms solid droplets in the still liquid higher-melting phase. Because these two phases invariably have different densities, they will rapidly separate as the droplets grow. The result is an almost complete stratification of the two metals.

A number of attempts has been made to prepare fine dispersions of the miscibility-gap alloy, aluminum-indium (Al-In), in space. These were generally unsuccessful until the means for controlling capillary flow were demonstrated. When surface tension differences were properly controlled by selection of container materials and reduction of impurities, the predicted fine dispersion was formed during solidification of a hypermonotectic composition in low gravity. The study of miscibility-gap alloys is important from a fundamental and a practical viewpoint; they represent a large class of potentially useful new alloys.

(4) Nucleation in Undercooled Molten Metal - Nucleation and rapid solidification of undercooled melts are also important phenomena that are of fundamental as well as practical interest, in the control of grain structure and, hence, mechanical properties. By containerless melting and solidification, wall-induced nucleation (that is, points on the cold wall where freezing of crystals begins) can be eliminated. This allows the melt to be cooled substantially below the normal freezing point before nucleation eventually occurs. Solidification under

these conditions is extremely rapid and can produce unique microstructures and noncrystalline solids, such as palladium-silicon-copper and iron-nickel-phosphorous-boron used in transformer laminations. These materials are thought to be similar to those produced by rapid quenching of thin samples by splat cooling except a thick sample can be processed.

c. Containerless Processing - The MPS program has kindled new interest in containerless processing, i.e., the ability to melt, solidify, or otherwise process a sample without physical contact with a container. There are a number of reasons for wanting to do this: the ability to measure physical properties of high temperature and corrosive materials; to produce ultrapure specimens; to form unique glasses from materials that are reluctant glass formers, either because of their corrosive nature or their tendency to crystallize when they contact the container wall; to study nucleation and the associated time-temperature-transition relations; to study the solidification of deeply undercooled materials; and to fabricate unique shapes without sagging or physical contact, such as highly concentric glass shells for fusion research.

Containerless processing may be carried out on Earth by two basic methods: free-fall facilities and levitation facilities. A free-fall facility, such as the drop tubes at MSFC offers true containerless and near-zero gravity conditions for a very brief time (at most a few seconds). Levitation facilities support the sample (more or less indefinitely) by means of a force applied without solid contact. Such forces may be electrostatic, electromagnetic acoustic, aerodynamic, or hydrostatic. One of the disadvantages of using levitation techniques on Earth is the fact that levitation does employ external forces which may in fact influence the experiment by inducing heating, stirring, or other undesirable effects. Also the applied forces are generally not true body forces but are applied to the surface. Therefore, the sample is still subjected to gravity-driven flows such as sedimentation and natural convection.

Containerless processing in space is essentially a free-fall technique; however, it is necessary to apply low-level levitation forces to compensate for microgravity accelerations and maintain the position of the sample relative to the furnace or experiment chamber. Although such forces may produce some of the extraneous effects encountered in levitation in one-g, the magnitude of such effects can be reduced by several orders of magnitude because of the reduced g-levels.

(1) Nucleation Studies - The elimination of container-induced nucleation has allowed very deep undercooling in excess of 500 C of small (millimeter-sized) droplets of some molten metals such as niobium (Nb) and its alloys. In fact, earlier predictions of the degree of undercooling that was thought to be possible for droplets of this size have been exceeded. Solidification at this degree of undercooling is extremely rapid, comparable to rates obtained by splat cooling of thin samples. Usually nucleation occurs at only one point, and a single crystal results. Small single crystalline silicon (Si) beads have been produced by this method, which may find applications in low-cost solar cells.

Since a melt undercooled to this degree solidifies so rapidly and under highly nonequilibrium conditions, it is possible to form unusual compounds that do not form from equilibrium melting. As mentioned previously, bulk samples of superconductors have been produced in this manner.

One of the major factors in the formation of noncrystalline solids is the time-temperature-transition on cooling. Many substances can be chilled rapidly enough by splat cooling to form a noncrystalline phase, but whether or not such phases can be formed by slow undercooling, which would be necessary to process bulk samples, is a matter of conjecture. In normal solidification, nucleation from the container wall virtually always limits the degree of undercooling that can be achieved. The theory of nucleation is not well-established and is difficult to test. The nucleation and growth of the solid phase in the absence of the container's nucleation sites are obviously an important research area.

(2) Glasses and Glassy Metals - By the elimination of nucleation associated with container walls, it should also be possible to extend the glass forming range of many materials, including some metals. This could result in some new and unique glasses with exotic properties. It may even be possible to delay nucleation long enough for the sample to lose sufficient heat that the latent heat of fusion is no longer capable of raising the material to the normal freezing temperature. The solidification of such undercooled samples is of theoretical as well as practical interest because of the unusual microstructures that may result. Experiments with gallia-calcia glass to control the index of refraction have been initiated.

(3) Containerless Forming - The ability to process an object with very weak constraining forces in the virtual absence of buoyancy forces and hydrostatic pressure offers new techniques for forming materials without physical contact. One process that is of great current interest is a study of the centering mechanisms that operate in the formation of concentric glass shells required for inertial confinement fusion experiments by the Department of Energy. Such shells can presently be made with sufficient precision, in sizes up to several hundred microns, adequate for present research needs. However, in order to provide fusion power on a practical basis, containment shells up to a centimeter in diameter must be produced with a high degree of precision at a low cost. At this time, not enough is known about the mechanisms that are responsible for causing the bubble inside of the glass sphere to center and produce a concentric shell. A better understanding of this process may indicate a method for scaling up the present process to produce larger size shells. On the other hand, if such a process is not feasible on the ground, the shell could be manufactured in space by containerless forming.

(4) Ultrapure Materials - The elimination of crucible contamination is beneficial in the preparation of ultrapure materials. It may be possible, for example, to purify melts by containerless evaporation if the impurities have higher vapor pressure than the host material. Use of the high vacuum associated with the spacecraft wake would be an additional benefit for such a process. Preparation of oxygen-free materials is of technological interest. For example, oxygen impurities in cobalt samarium magnets may be responsible for limiting the magnetic strength of the material. The source of the oxygen is suspected to be the crucible material; therefore, added performance might be derived from containerless melting in an electromagnetic levitator.

A most important application for the preparation of ultrapure material could be the production of ultrapure glass for use in optical wave guides for high frequency communications. Although extremely high purities have been achieved with quartz using the chemical vapor deposition process currently employed for production of optical fibers, the cost is high and the types of glasses that can be produced are limited. With containerless processing, it may be possible to use a broader range of glasses that are less expensive or have different optical properties but tend to pick up trace crucible contaminants because of their chemical activity.

d. Fluids and Chemical Processes - Although the gravitational contribution to chemical reactions is usually negligibly small, many processes are controlled by mass and heat transport which are affected by gravity-driven convection or sedimentation. Often this occurs in complicated ways in which gravity-driven flows are coupled with nongravitational flows such as surface tension-driven convection. Experiments in low-g can simplify such problems by eliminating one set of flows so that the nongravity components may be isolated and studied with a degree of freedom not otherwise possible.

In some processes, it is desirable to keep a component in suspension in order to study nucleation and growth of one phase. By eliminating convection, other transport studies can be made tractable. By eliminating the hydrostatic pressure, free and interfacial surfaces are controlled only by surface tension. This greatly simplifies the study of wetting and spreading and the measurement of contact angles, especially near critical phase transitions where interfacial tension approaches zero. Also, the usually insignificant gravitational contribution to thermodynamic properties is not negligible near a critical phase transition because many terms go to zero. Therefore, there are advantages in studying critical point phenomena in a low-g environment.

(1) Surface Tension Driven Convection - One of the major driving forces for convective flow in the absence of gravity is surface or interfacial tension. There is considerable interest in understanding this phenomenon.

Such flows are expected to play an important role in a number of processes. For example, the thermal migration of bubbles or droplets is driven by temperature variation and surface tension. These flows may be important in getting rid of bubbles in glass or coalescing particles in phase separations. On the other hand, this could also be an unwanted mechanism that causes phase separation in the preparation of some alloys. It is also suspected that surface-tension flows play an important role in flame propagation in flammable liquids. The lower-surface tension near the flame causes fluid to "pull away" from the flame, resulting in a slight depression. The return flow feeds fresh fluid from beneath the surface into the flame.

Perhaps the most compelling reason for studying surface-tension convection is its importance in floating zone crystal growth. This process involves free surfaces and large temperature gradients. The convective transport in a unit gravity field is very complicated. Performing such experiments in a low-g environment provides a method for simplifying the flows by eliminating the buoyancy-driver effect, thus isolating the surface tension effects.

(2) Critical and Interfacial Phenomena - Since the difference between the many thermodynamic properties of two phases vanishes at the critical point, the small contribution from the difference in gravitational potential may become significant. Also since the density of the two phases is virtually always different, gravitational sedimentation will cause rapid phase separation. This limits the time over which the transition can be observed on Earth.

As systems that have two immiscible liquid phases approach the transition to a single liquid phase, the interfacial tension goes to zero. Theory predicts that one of the phases becomes perfectly wetting at the critical point. This is difficult to observe in the laboratory. The existence of one phase that becomes perfectly wetting may be the key to the rapid phase separation observed when attempting to form certain alloys.

(3) Polymerization Phenomena - There are a variety of processes important to industrial applications that may be studied in a low-g environment for the purpose of understanding the role of gravity effects or for taking advantage of the virtual lack of buoyancy-driven convection, sedimentation, or hydrostatic pressure in order to achieve better process control. For example, seeded polymerization of latex may be used to grow monodispersed spheres in a size range that is virtually not achievable by ground based techniques because of creaming or sedimentation effects. Such spheres would be useful as standards for calibrating counters, sizing membranes, and possiblyother biomedical applications.

The absence of gravitational forces provides an opportunity to study the role of chemical fining (bubble removal in glass) by eliminating buoyancy motion. Chemical fining agents certainly will become more important in the future as energy costs continue to rise. Because glass is viscous, velocities of bubbles are extremely low, and very long, high temperature soaks are required. Chemical finers are known that help reduce the time, but the mechanism is not well understood. It is difficult to contain a bubble in a small container for study on Earth.

Another endeavor that takes advantage of the absence of sedimentation is the study of Ostwald ripening used for strengthening alloys. This is a process by which second-phase particles evolve into a distribution of sizes with the larger particles growing at the expense of smaller particles. This effect is quite important in metallurgy where the size of a precipitated second phase is altered by heat treating. Although the phenomenon of Ostwald ripening has been known for a number of years, there is no satisfactory agreement between theory and experiment because of the difficulty of maintaining stable suspensions of the precipitating phase on Earth.

(4) Electrochemical Deposition - Electrochemical deposition is a process that is influenced considerably by gravity because of internal heating of the bath as well as convection from concentration gradients. Yet little work has been done to understand the role of gravity-driven fows. In some cases it is desirable to incorporate inert particles of a second phase into an electroformed product to improve its properties. Maintaining such particles in a suspension and incorporating them uniformly into the structure is difficult in the laboratory. Low-gravity electroplating experiments have been initiated.

(5) Biomedical Applications - A number of processes of interest to the biomedical community that are adversely influenced by gravity effects have been identified. These include electrophoresis, isoelectric focusing, phase partitioning, suspension cell culturing, crystallization of macromolecules, and the study of blood flow. Experiments performed in space can provide valuable insight into the control of the processes on Earth, produce research quantities of unique products, and eventually develop unique separations or products on a preparative scale. A joint endeavor with an industrial firm is evidence of the potential economical benefits that can come from bioprocessing in space.

(a) Separation Processes - Separation of complex material mixtures into their component parts is a goal of extreme importance in many fields but is of particular importance in the various biomedical fields. Indeed, the lack of satisfactory techniques for such separations is now in many cases the limiting factor that impedes further research progress. The kinds of biological components in need of improved separation methods include cells, cell components, and macromolecules.

Every organ of the mammalian body is made up of a great variety of functional cell types, which can frequently be best studied in homogeneous populations of a single cell type. However, cells that differ importantly in their functions are often so similar in their size, density, and appearance that it is impossible to obtain a pure population of any one cell type by conventional separation methods (density gradient centrifugation, for example). In addition to facilitating basic research into normal and abnormal cell physiology, improved cell separation methods could conceivably be used to provide purified cell

populations for transplantation into individuals lacking normal cells of that type. Also purified populations of cells that secrete valuable products could be most useful in the commercial production of these substances, because cell culturing processes could be greatly simplified and their efficiency increased by selecting only active, producing cells for culture. The kidney cell separation experiments on Apollo-Soyuz provided a step in that direction.

Purifying macromolecules that have been synthesized is another application of bioprocessing separations technology. Some macromolecules must be laboriously purified from heterogeneous medium such as blood, urine, or tissue. Other macromolecules can be obtained through cell culture, recombinant-DNA technology, or artificial peptide synthesis. In each of these cases, however, the final product is not pure but rather a complex mixture requiring extensive purification. In addition, neither recombinant-DNA technology nor laboratory peptide synthesis can be performed until the desired product has been obtained in strictly pure form in sufficient quantity to allow determination of its molecular structure. For many important macromolecules (e.g., interferon, alpha-1-antitrypsin), this has been impossible to achieve in spite of the many techniques presently available. Methods currently employed for the purification of complex mixtures of macromolecules include ultracentrifugation, filtration and chromatographic (preferential adsorption) methods.

One important fact to consider is that most current cell separation techniques are based either on very nonspecific characteristics of the cell (e.g., density) or on characteristics so highly specific that the method can be used only on previously purified populations of cells. A purified cell population must first have been obtained. Because of these limitations, existing techniques are either quite nonspecific, or else they are "circular" in that it is necessary to possess a purified population before one is able to obtain a purified population. In contrast, both continuous-flow electrophoresis and phase partitioning avoid this liability; with either technique, it is possible to begin with a mixed population of cells about which one knows essentially nothing and to sort them into categories which are specific as well as biologically meaningful. However, both of these methods appear to be significantly impeded by gravity-related effects. Therefore, free-flow electrophoresis and phase partitioning could conceivably provide unique advantages over other techniques if such separations were carried out without the perturbations introduced by Earth's gravity.

1. Electrophoresis - Electrophoresis is a well known technique separation of proteins and other macromolecules on an analytical scale. Such molecules acquire a specific charge when immersed in a buffer solution. An applied electric field interacts with this charge and produces a force which moves the molecule against drag encountered in the medium. This allows materials with different mobilities to be separated.

On Earth, electrophoresis is usually carried out in the presence of a gel to prevent convective mixing. This restricts the quantities that can be separated and precludes use of the technique for cells. One

technique for circumventing this restriction is the use of free-column electrophoresis, using vertical columns with a density gradient to stabilize the fluid motion. In this system, the cells migrate against gravity. Although this technique has enjoyed only limited success, it was a first choice for space where density gradients are not required.

Experiments performed on Apollo-Soyuz showed some indication that kidney cells could be separated according to function. One fraction of cells, when cultured, showed a significant enhancement in the production of the valuable enzyme urokinase. Column electrophoresis can be a very valuable tool for space use for obtaining extremely high resolution separations of research quantities of material.

Another means of obtaining electrophoretic separation of cells or macromolecules is the use of continuous-flow electrophoresis (CFE). By its nature, free-flow electrophoresis is associated with significant problems, many of which are gravity determined. The passage of the electric current causes heating which tends to produce unwanted thermal convection, impairing the resolution of the separation. Sedimenation of the sample material limits the concentration of the sample and thus the throughput. The CFE instruments currently in use are stabilized by using a very thin flow channel to suppress convective flows. This limits throughput and resolution because the sample stream is subject to distortion from wall effects. To determine the benefits that may be obtained by operating in space as well as the most advantageous design for such devices, it was necessary to study the fluid dynamics of electrokinetic separation. It has now been found that most of these difficulties can be avoided in a low-g environment where the buoyant forces would be dramatically lessened. There may be other effects that limit the performance in low-g, but it does appear that there is a good rationale for a flight experiment to explore the effects that are overshadowed by convective problems on the ground.

2. Isoelectric Focusing - In isoelectric focusing, a pH (H + ion concentration) gradient is set up by an applied electric field upon electrolytes added to the buffer solution. The material to be separated is driven by the electric field to a region of pH known as the isoelectric point, where the electrophoretic mobility of the sample is zero. Very high resolutions are possible because the boundaries of the sample bands are self-sharpening. This is a particular advantage when dealing with proteins or other macromolecules because the focusing process counteracts diffusion. Isoelectric focusing is subject to gravity-induced convection and sedimentation problems.

A novel isoelectric focusing machine was recently developed as a potential space experiment. This machine is a recirculating device with a number of fluid loops that come together in a common chamber. The electrolytes migrate through membranes in the chamber to form a stepped pH gradient in the various flow channels. Once the pH gradient has stabilized, the

biological sample is introduced and each component migrates to the channel corresponding to its isoelectric point. A ten-channel machine has been built and demonstrated to be capable of separating a number of test materials. It is believed that the membranes could be eliminated entirely by performing the separation in low-g.

The device has attracted considerable attention in the biomedical community, and a number of reseachers have delivered samples to be separated. It has been suggested that high-resolution, high-throughput, continuous-flow isoelectric focusing would be a useful method for purifying natural or synthesized products such as polypeptide hormones, interferon, recombinant-DNA products and other macromolecules.

(b) Blood Rheology - Blood is a fluid with a viscosity that is strongly dependent on shear rate. This fact is due primarily to the presence of the red cells. The rheology (study of flow) is further complicated by the fact that red cells form aggregates, of varying sizes in different physiological conditions. Coagulation may occur in addition to rapid sedimentation of aggregates. Rheological considerations appear to be important in several disease states, including cardiovascular disease, diabetes, sickle-cell anemia, and some forms of kidney disease. For example, sedimentation of red blood cells is more pronounced in a variety of pathological conditions, and it forms the basis for clinical tests. One question is raised as to whether the cellular aggregations in pathological conditions seen in the laboratory produce a different pressure drop across a blood vessel. Simultaneous sedimentation precludes an answer to this question. An increase in the pressure drop merits appropriate countermeasures, whereas a decreased pressure drop would constitute a beneficial situation. Obtaining a thorough understanding of the rheology of blood is extremely important. However, the examination of biological cell dispersions in laboratory viscometers is rendered problematic under terrestrial conditions by sedimentation. Research in a reduced-gravity environment to alleviate these problems has been proposed.

e. Extraterrestrial Materials Processing

(1) Goals - The long range goal of space materials science is to provide for the cost-effective use of extraterrestrial materials resources for both space systems and terrestrial applications. This goal requires the demonstration of advanced autonomous and teleoperated machinery for remote operations. The machinery must have a high degree of self-sufficiency and self-replication. The remote operations include exploration, acquisition, staging, conversion, manufacturing, assembly and construction of facilities. The goal also requires demonstration of space-adapted techniques for acquiring and converting raw materials occurring in space into useful forms for space and terrestrial applications.

(2) Development - Development of technology along several parallel fronts is required to accomplish the goals. Exploration of the moon, asteroids and planets will locate the needed mineral supply in terms of distribution and concentration and characterize it in terms of chemical and physical properties. Development of technology in space systems will provide the materials, structures, machine intelligence, robotics, energy systems and transportation systems to reach the goal. Plans for coordination of activities leading to a phased development of a system demonstration are being defined. The first phase will involve project planning, resource evaluation, materials analysis and materials processing experiments. The second phase will involve breadboard demonstrations on individual system components, such as an Earth demonstration of an automatic reducing cell to process lunar or asteroid material into aluminum and/or silicon, and an Earth orbital demonstration of elements of the space materials processing system for concept verification. The third phase will involve designing and building actual space systems hardware, testing and mission operations. A steering committee is currently working on the details of this effort.

(3) Status - Currently, hardware components are being developed in biomedical applications, spacecraft remote deployment and retrieval of experiment packages, and by adaptation of remote manipulators from Surveyor and Viking planetary spacecraft. In the area of intelligence, very large scale integrated circuits are being applied with increased hierarchy to control industrial processes. These can be adapted, directly. Materials processing techniques are being examined for adaptivity to space systems. Finally, for planning purposes, self-replicating algorithms are being formulated.

(4) Plans - Planning is being done to provide for automation of the deployment and operation of free-flying materials processing payloads. Computer control of spaceflight payloads is being decentralized to enhance flexibility, changeout, learning capabilities and independent decision making on individual payloads. Research is directed toward a better understanding of materials processes, including scaling laws and nonlinear phenomena and to development of the best space processing methods for extraterrestrial materials. System engineering is being employed for analysis of competing scenarios.

2. Privately Funded Commercial Activity

The ultimate goal of the MPS program is to develop a viable commercial interest in using space: (1) to perform zero-g research to improve industrial technology or to develop new products on Earth, (2) to prepare research quantities of material in zero-g to serve as paradigms with which to compare current Earth-based technologies and (3) to produce specific materials in space of sufficient quantity and value to stand on their own economically.

It is recognized that it will be necessary for NASA to provide the impetus for demonstrating to potential industrial users that they can learn more about their process by conducting experiments in space as well as doing things in space that they cannot do on Earth. This can best be accomplished by working closely with industries to the point of understanding their problems sufficiently to

identify areas in which materials science and engineering can best be utilized. It is probably not realistic to expect major commitments from industry alone until NASA has completed a sequence of spaceflight opportunities and has been given a chance to demonstrate the potential that space offers. Also, ways must be found to select experiments for flight, protect the proprietary rights of the customer, reduce the lead time, and lower the costs of conducting experiments in order to attract the private industrialist.

An important first step is the establishment of joint projects, with varying levels of involvement, with industrial users to assist them in exploring areas where MPS can be utilized to meet their own needs. In general, these joint projects are envisioned to be "constructive partnerships" between NASA and industrial firms wherein the parties are seen as equals who have common objectives. Also arrangements are being worked out to lease existing NASA facilities and for cooperative development facilities. Increasing commitment on the part of the user will be required as the project matures.

The Commercial Applications Office, MPS Projects Office, MSFC, has been created to work exclusively with commercial interests. This team forms a bridge between NASA and the commercial community, serving as a source of information and assistance for the user as well as a focal point for commercial views and a channel by which these views can be articulated to NASA. This team is also working to obtain clarification of patent protection rights, proprietary rights, liabilities, leasing policy, and pricing. It is through this effort that NASA believes it can provide a simpler interface to the private sector, develop a better understanding of the incentives needed to elicit private initiatives, and to stimulate the inventive genius and entrepreneurial spirit in this country to fully utilize the benefits to be derived from the MPS program.

Joint projects between industry and NASA are not government procurements but rather agreements to cooperate in a defined area with specific tasks to be accomplished by each party. They are expected to evolve with increasing interest and responsibility on the part of the industrial partner. Commercial MPS has three levels of working relationships to provide for incremental increase in commitment by the parties involved. They are:

- Technical Exchange Agreement (TEA)
  - Cooperation in analysis of data and specimens from ongoing research
- Industrial Guest Investigator (IGI)
  - Collaboration with a NASA-sponsored Principal Investigator (PI) of a flight experiment
- Joint Endeavor Agreement (JEA)
  - Investment by private enterprise sharing in the cost and risk of an early space venture

Discussions with key people in over 150 companies, both large and small, have initiated many MPS industrial research tasks in the private sector. Private companies do not publicly announce their interests and they usually request anonymity in their initial working relationships with NASA. However, some agreements have been publicly discussed:

- o A TEA is being culminated by Deere and Company in the field of solidification of metals
- o An IGI was formally appointed in May 1980 by TRW Equipment Division in Cleveland, Ohio, in the discipline of directional solidification
- o A JEA was signed in January 1980, with McDonnell Douglas Astronautics Company (MDAC), developer of the biochemical separation equipment, who is teamed with Ortho Pharmaceutical Division of the Johnson & Johnson Company. The equipment is being evaluated for isolation of materials such as hemophilic factor VIII for hemophilia, beta cells for diabetes, alpha-antitrypsin for emphysema, epidermal growth factor for healing burns, growth hormone for stress ulcers, immunoglobulins for hepatitis, summatomedin for meat production, transfer factor for melanoma, and urokinase for blood clotting. This initial endeavor has been the subject of testimony to congressional committees in both the U.S. House and Senate.

Other offers of cooperative agreements in various stages of discussion include:

- o A TEA with a major metallurgical supplier on electrodeposition
- o A TEA with a university research institute and a pharmaceutical company to evaluate purification of proteins in a new device
- o A TEA with a major electrical equipment supplier on dispersions of immiscible materials
- o A JEA with a nonprofit research institute to grow a biological material for assisting the repair of human tissue
- o A JEA with a new high technology oriented small business to develop semiconductors
- o A JEA with a small materials research business to provide research samples to industry

B. Institutional Structure

1. NASA Program Management

The NASA MPS program is the responsibility of the Associate Administrator for the Office of Space and Terrestrial Applications (OSTA) and is directed and administered by the Director, MPS Division, at NASA Headquarters (Figures 1 through 3). The Division Director is supported directly in the overall management and execution of the program by the MSFC MPS Projects Office (Figures 4 and 5) and other NASA centers. The projects office depends upon the laboratories of MSFC, other government agencies, universities, institutions, and the private sector for technical support and program implementation.

In consonance with the recommendations of the Scientific & Technological Aspects of Materials Processing in Space (STAMPS) committee, a scientific advisory committee has been formed, responsive to the MPS Division Director, to aid in future program planning and policy making 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.

The Director, MPS Division, OSTA, determines program policy, objectives and priorities, and controls the allocation of program resources. OSTA is additionally responsible for science policy, objectives, and priorities, and for soliciting, evaluating, and selecting MPS flight investigations.

The MPS Division maintains full visibility into project level activities through participation in milestone reviews, receipt of regular and special reports, control of Level I changes, and informal information exchanges with all levels.

Integration and mission management activities associated with the operational implementation of MPS payloads on the STS are the responsibility of the Spacelab Mission Integration Division, Office of Space Science (OSS), in NASA Headquarters and the assigned Mission Management Center, when applicable. The MPS Projects Office at MSFC provides the necessary interface and support to the Mission Management Office for initiation and execution of mission requirements. The MPS Projects Office also provides the Mission Manager with appropriate project data to assure successful integration of approved MPS payload systems into the Space Transportation System (STS) and their operation as payloads. Level IV integration requirements for MPS payloads are mutually agreed-to by both the Mission and MPS Projects Managers. The MPS Projects Office also provides the Mission Manager with the launch site and flight requirements for MPS payload systems. The MPS Projects Office also furnishes mutually

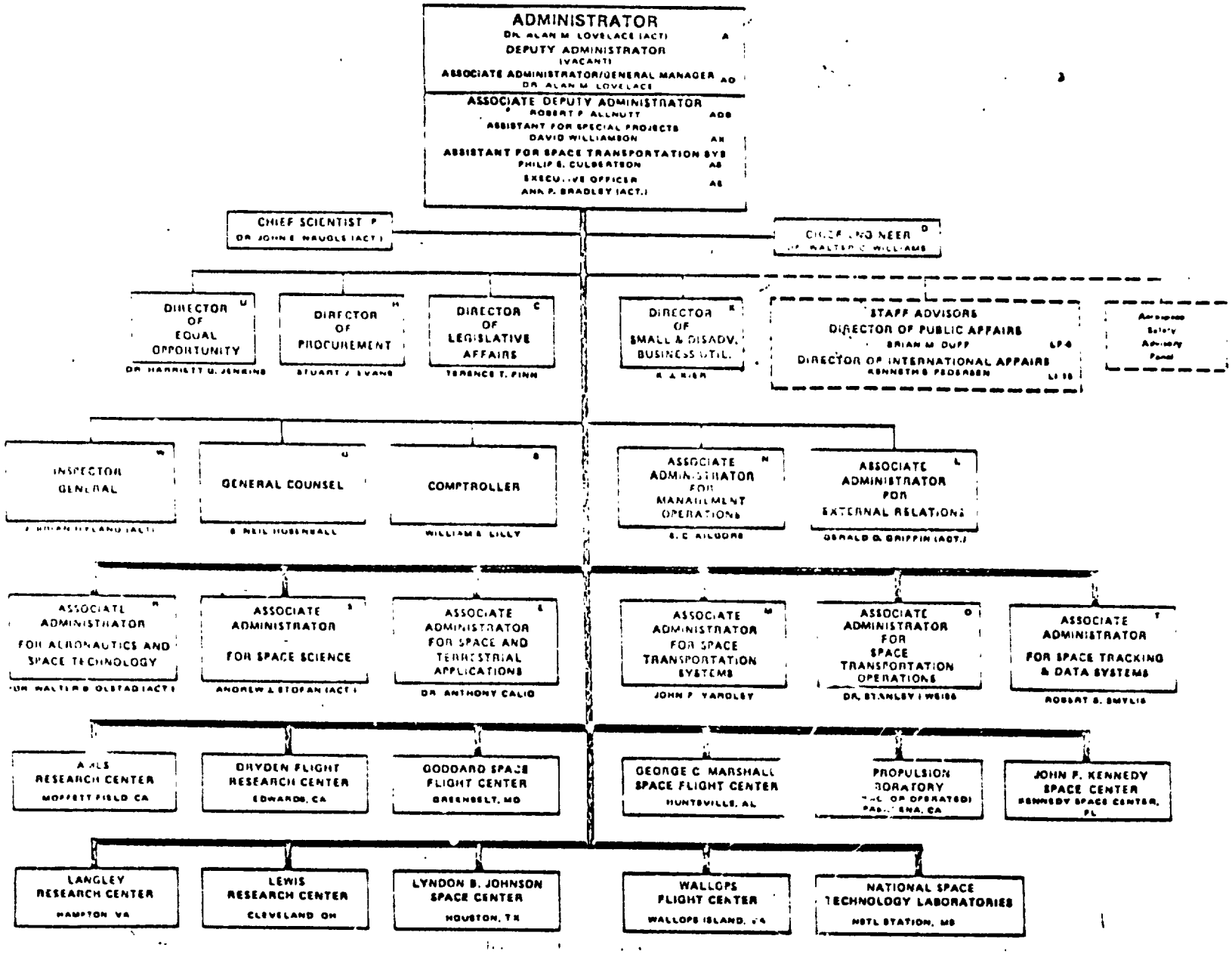

FIGURE 1

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OF POOR QUALITY

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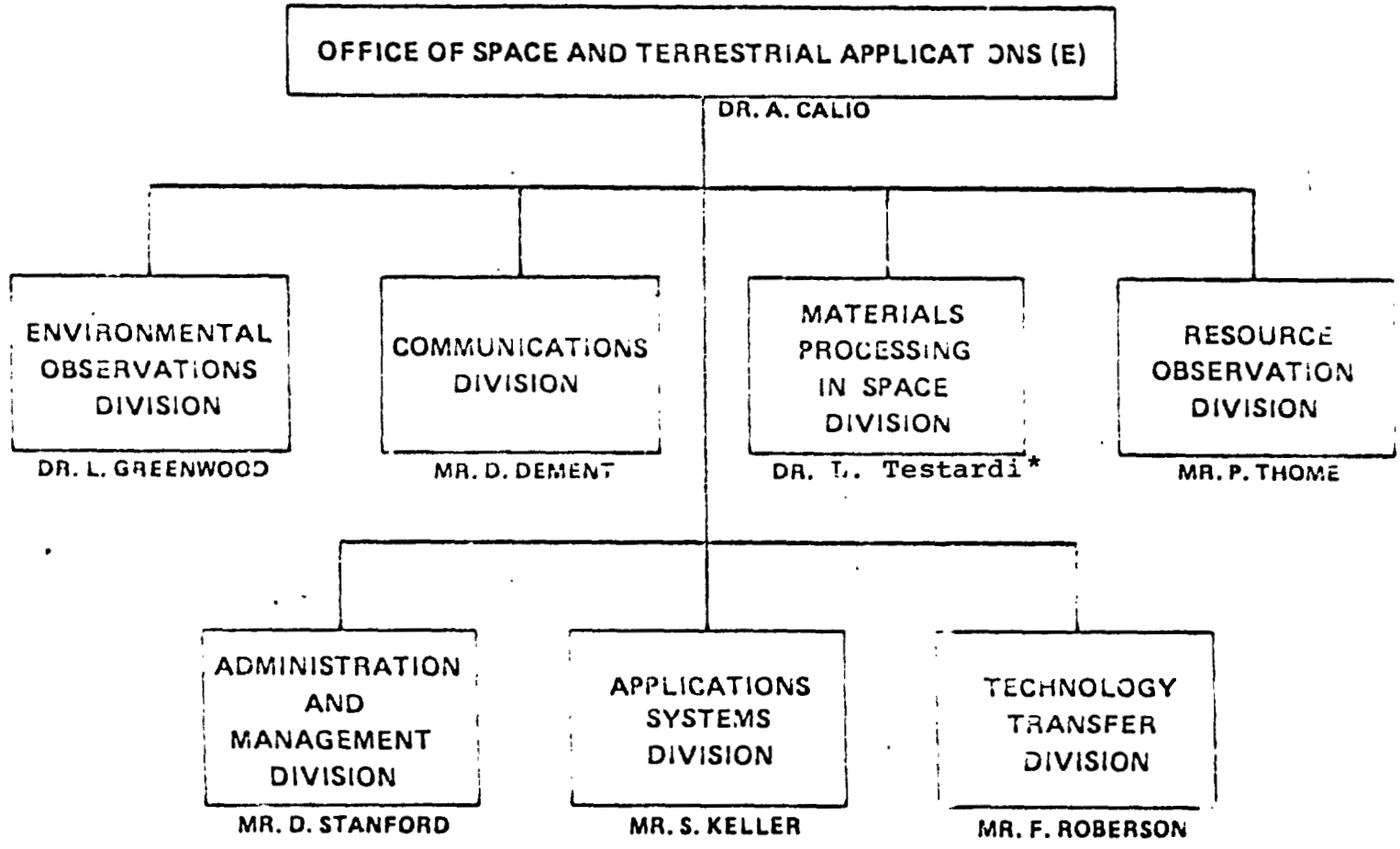

FIGURE 2

* Acting

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FUNCTIONAL CHART
MATERIALS PROCESSING IN SPACE

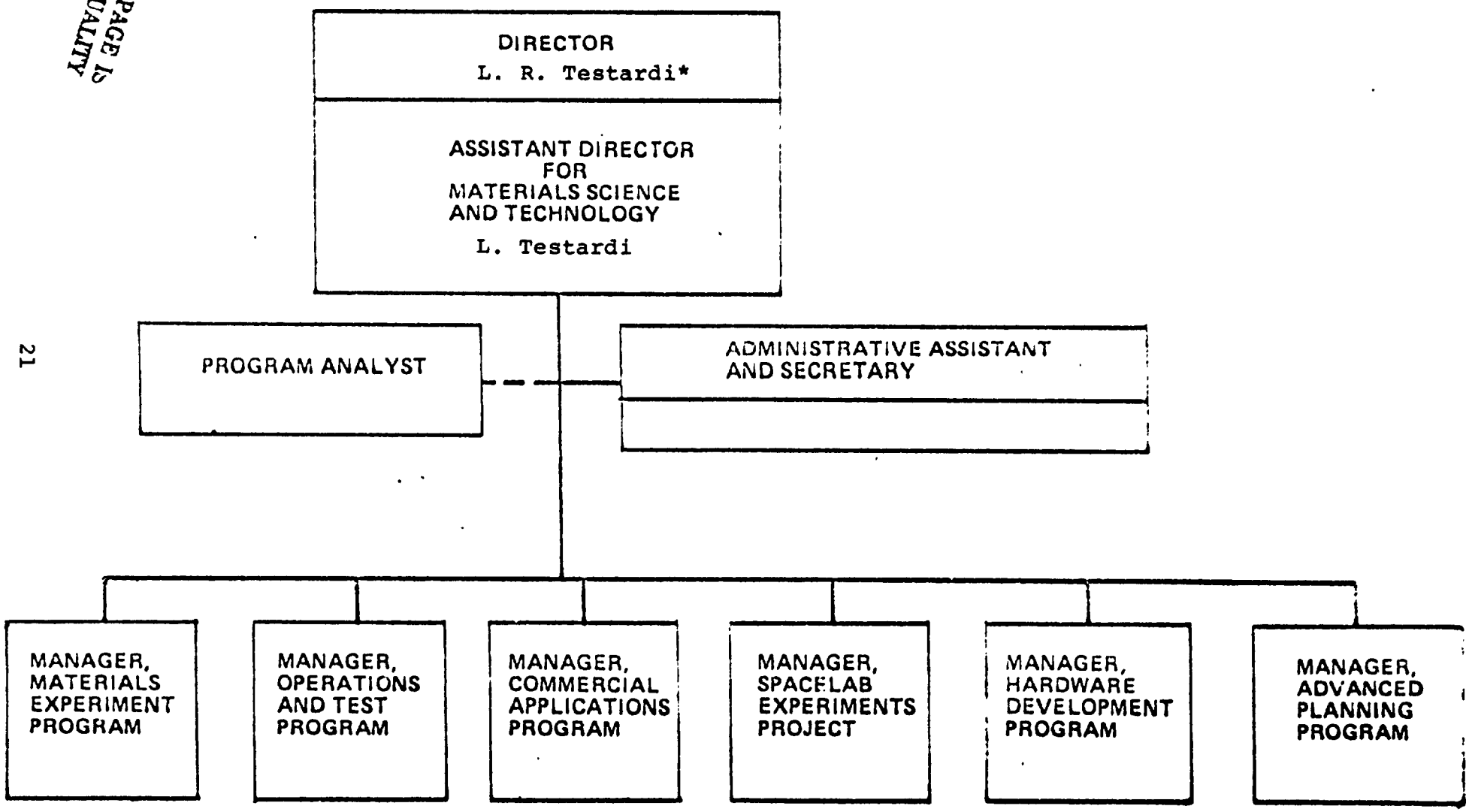

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FIGURE 3

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

GEORGE C. MARSHALL SPACE FLIGHT CENTER

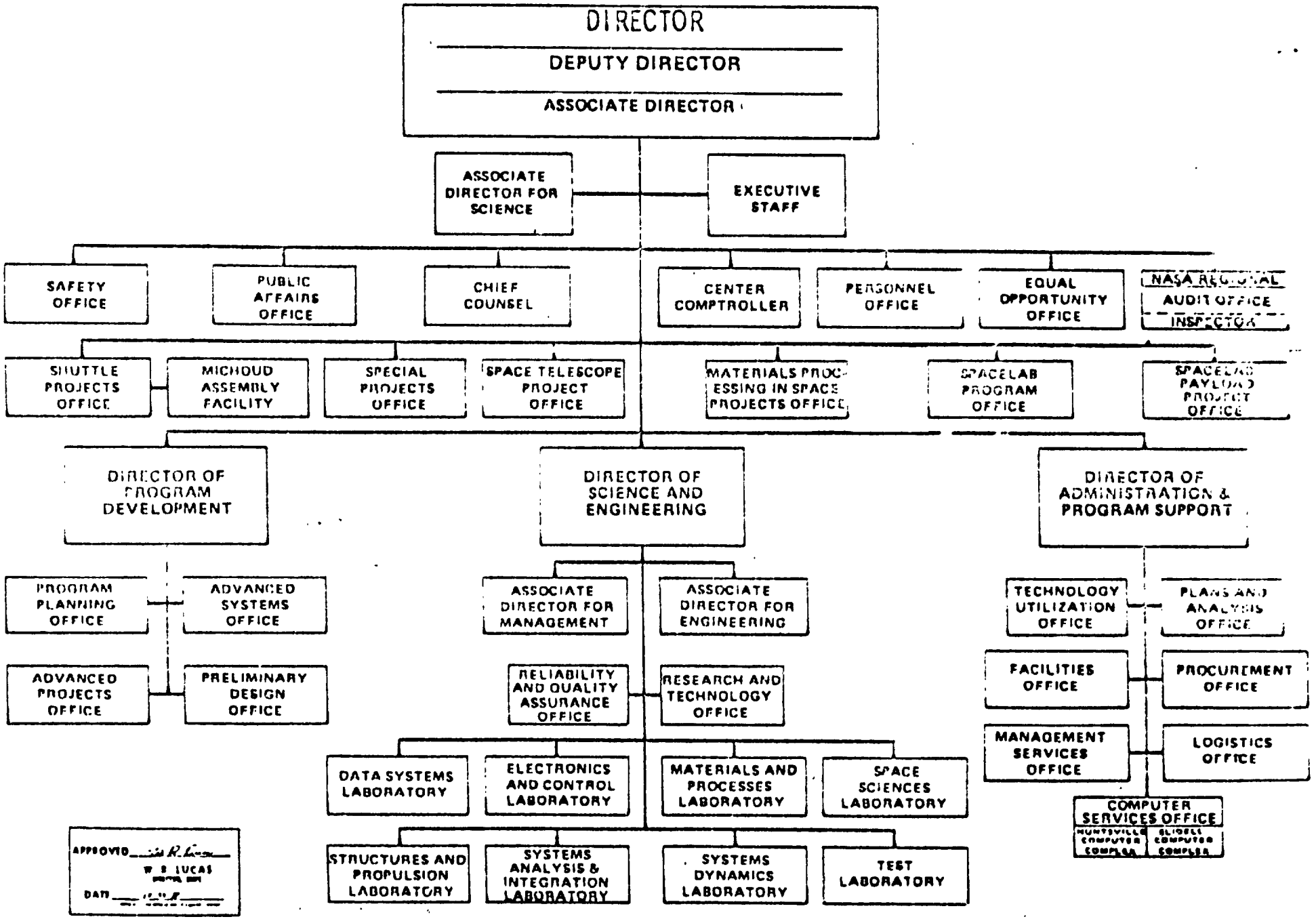

FIGURE 4

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MARSHALL SPACE FLIGHT CENTER
MATERIALS PROCESSING IN SPACE PROJECTS OFFICE

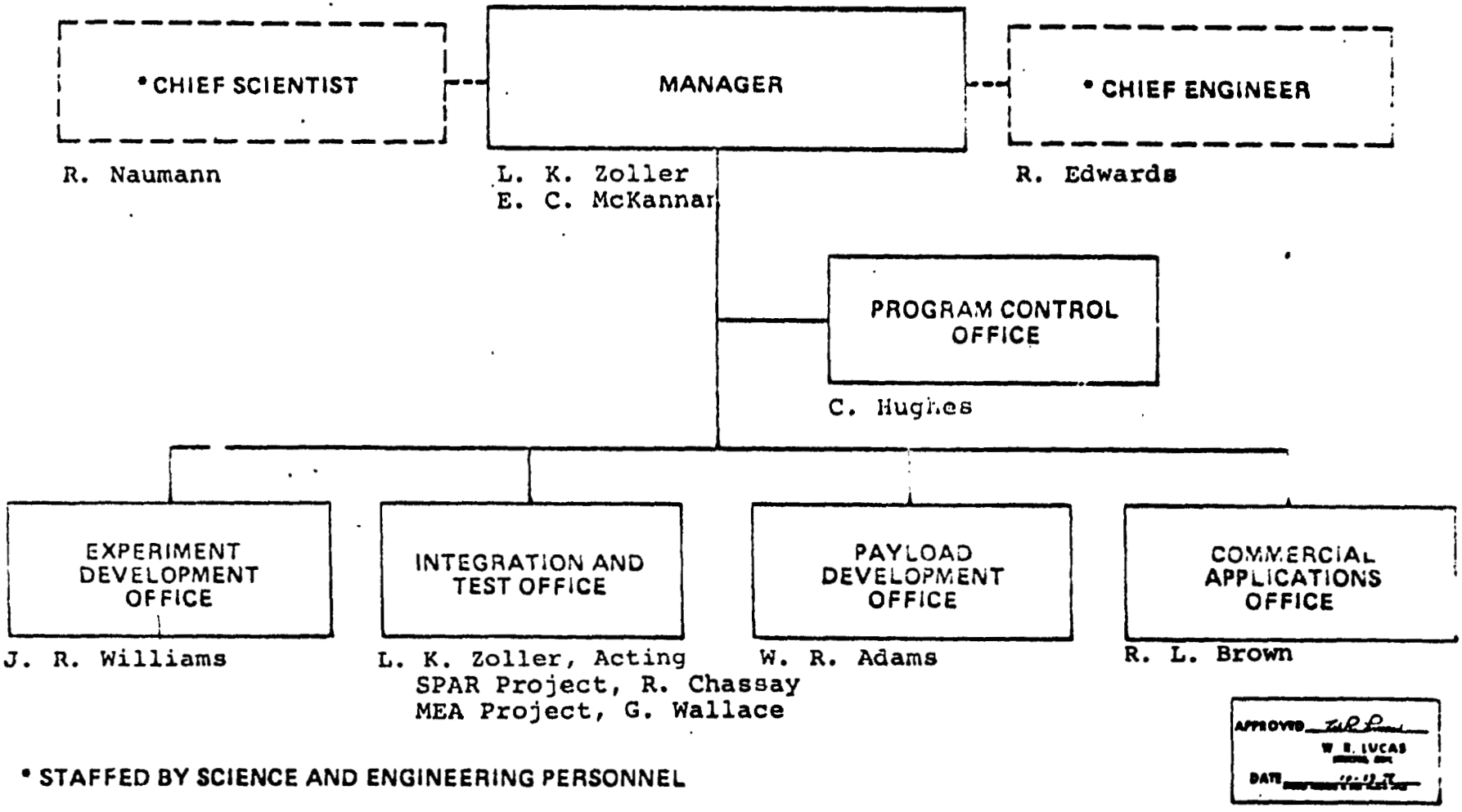

FIGURE 5

agreed-to support for launch site integration, prelaunch and flight operations phase of activities for operations involving MPS payload equipment. These services will be funded by the MPS budget.

NASA in-house research is conducted in several centers, primarily the MPS Division of Space Sciences Laboratory at MSFC and at several technical laboratories at the Jet Propulsion Laboratory (JPL). JPL organization charts are included as Figures 6 and 7.

Smaller research groups at Johnson Space Center, Lewis Research Center and Langley Research Center participate to provide specific expertise.

2. Academic Participation Proposal Process

NASA relies heavily upon the scientific community, both industrial and university, for the generation of concepts through proposals, and direction and review through committees. The National Academy of Sciences Committee on STAMPS provided consultation and recommendations for proceeding into the future. Peer groups made up of industrial and university scientists meet periodically to review the results of research activities.

Unsolicited proposals are entertained for studies, theoretical and experimental research, or minor developments carried out at the investigator's institution. These projects may include experiments which use available NASA facilities such as drop towers, aircraft, or sounding rockets.

Opportunities for ground-based research are described in Applications Notices (AN's). Proposals for ground-based research may be submitted at any time, and they are reviewed at least three times per year.

Spaceflight experiments must be proposed in response to specific Announcements of Opportunities (AO's). AO's are synopsized in the Commerce Business Daily. However, prospective proposers may also request the MPS Projects Office to include their names on the AO mailing list. Guidelines for proposing spaceflight experiments are generally similar to those for ground-based research, though somewhat more elaborate. They are included in each AO and specify not only content but the format in which the information is to be submitted. The AO process assumes that a substantial degree of ground-based research has been performed and that such work is sponsored through the ground-based research program or some suitable equivalent.

Each proposal undergoes a peer review to determine its scientific and/or technological merit. In addition, the reputation and interest of the investigator's institution, cost, and management will be considered by the Center Projects Office. AO's indicate other specific evaluation criteria and the relative importance of all criteria used in evaluating proposals.

JPL SPACE PROCESSING PROGRAM ORGANIZATION

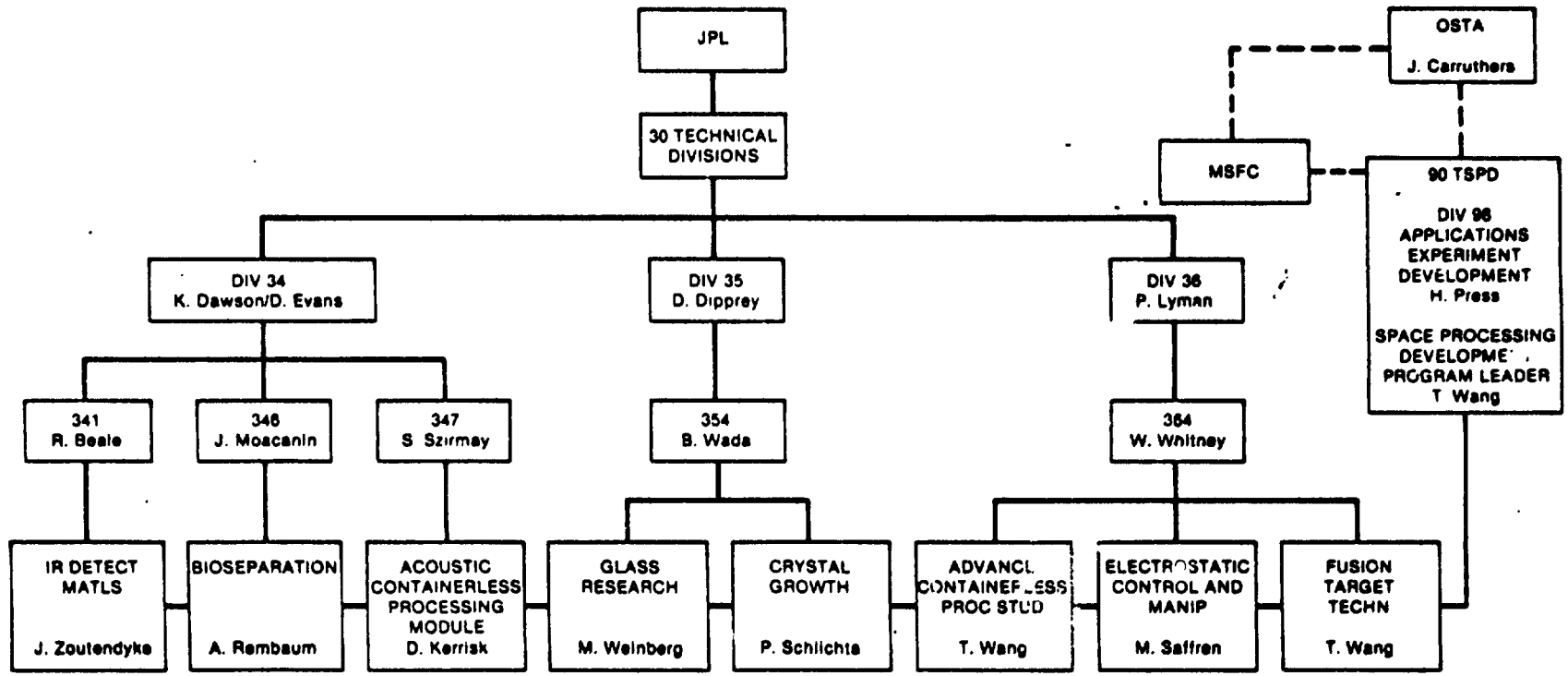

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FIGURE 6

JPL ORGANIZATION

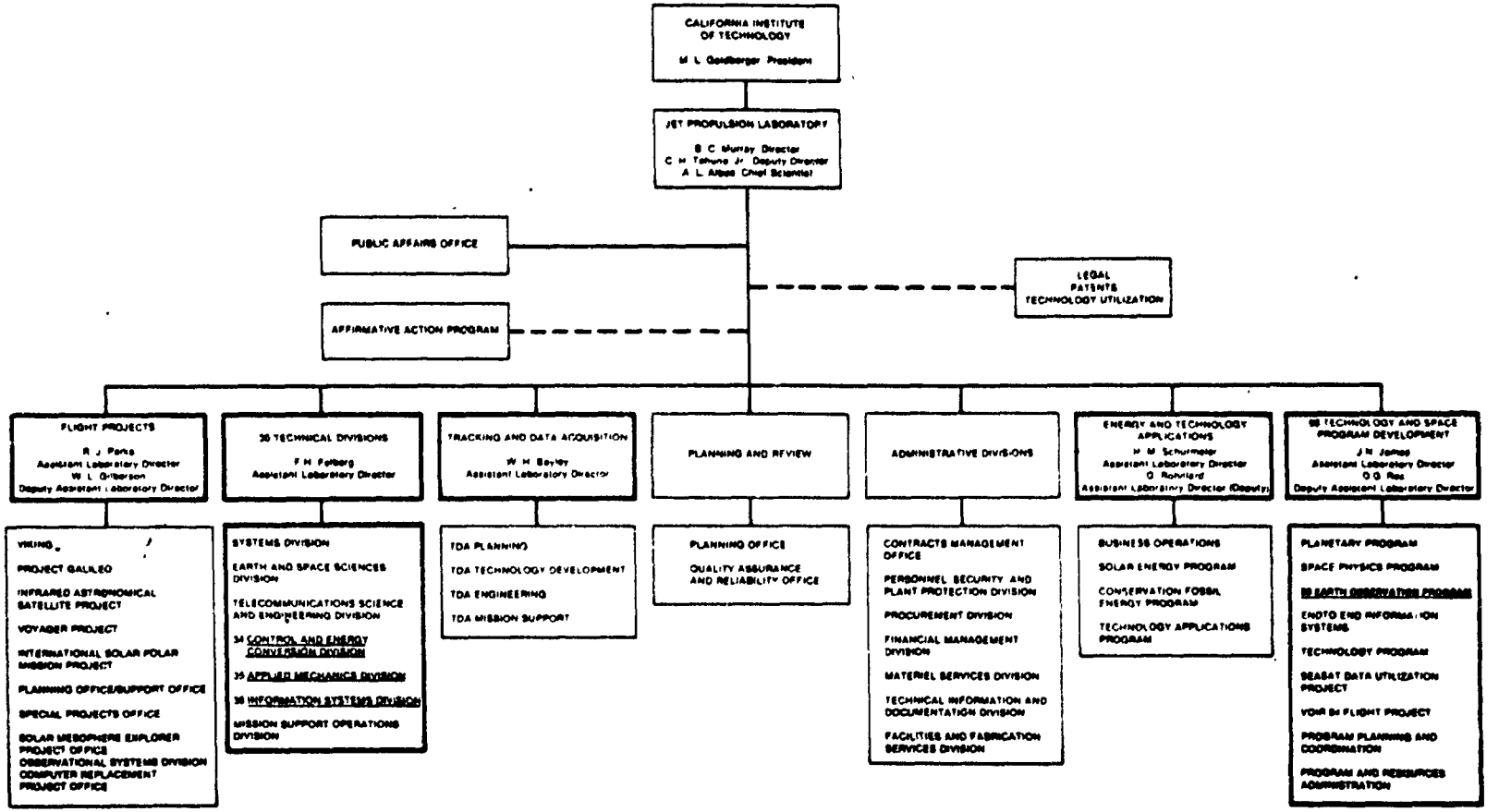

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FIGURE 7

The scientific evaluation is performed by a proposal evaluation committee composed of scientists who are doing research in materials processing. There is at least one member who is active in each of the major disciplines of materials processing. Care is taken in the selection of committee members to avoid any type of conflict of interest concerning the proposals under consideration. Lead review responsibility for each proposal is assigned to the member most qualified in the involved discipline. That member selects other scientists from the discipline to assist in the confidential review of the proposals for which he is responsible. These other scientists also are screened concerning potential conflicts of interest. However, the control of this distribution of the proposals is the responsibility of the designated committee member. Each committee member develops a set of recommendations concerning the proposals of his particular discipline(s). The committee then compares the relative merits of proposals between disciplines to produce an overall set of recommendations. During this process, no information concerning the proposals is revealed to anyone outside the committee or related NASA personnel.

Each proposal is then thoroughly reviewed concerning engineering, integration, management, and cost. An assessment is made of the development risks for those proposals requiring instrumentation. Evaluation of the proposals under final consideration includes workload (present and anticipated) related to capacity and capability, past experience, and management approach and organization. This ensures that the investigation can be managed, developed, and executed with an appropriate probability of technical success within the estimated cost.

The final determination made by NASA balances all of the above evaluations with respect to developing a program which maximizes the probable scientific return within a reasonable time and within budgetary constraints. Therefore, judgements concerning the most promising discipline areas are made.

Investigators whose proposals are not selected are notified of that fact together with a description of the major reason(s) why. Such proposers may also request a detailed oral debriefing after the selection process is completed. A proposal which has not been selected under a given review may, if agreeable with the proposers, be held for later consideration and funding.

Letters of notification are sent to those PI's selected to participate. Each letter contains a description of the PI's investigation as selected, specifically noting substantive changes, if any, from the investigation originally proposed; an indication of whether it is a final selection or a tentative selection requiring additional hardware or cost definition; a description of the PI's anticipated role, particularly with respect to providing instrumentation; identification of areas to be negotiated; rights to be granted to use of data; and, where applicable, indication that a foreign selectee's participation in the program will be arranged between the Office of External Relations and the foreign government agency which endorsed the proposal.

Experimentation in space is viewed as an extension of ground-based research, thus representing an additional research tool. As ground-based research in a particular area progresses, a point may be reached where it can be clearly identified that important unresolved questions could be answered by resorting to experimentation in space. It is at this point that definition of a flight program warrants initiation.

Flight program conceptual definition will entail two parallel activities: experiment definition and hardware definition. For this purpose, science working groups (SWG's) will interact directly with a contractor regarding the definition of experiment hardware requirements and specifications. The SWG's will define the scientific aspects of experiments to be performed in space and all related requirements of the conceptual experimental hardware. These requirements are to be based on laboratory experience.

SWG's should generally.

a. Become cognizant of (and help generate) relevant scientific investigations and help mature these investigations into meaningful low-gravity experiments.

b. Foster interactions among investigators, contractors, engineering, and programmatic elements so that a scientific rationale will guide each MPS-funded project.

c. Ensure that the investigators work closely with the hardware engineers to develop the advanced technology/apparatus needed for a meaningful, evolutionary, low-cost program using a spectrum of facilities from drop towers to Shuttle-orbited payloads.

d. Define science performance requirements or ranges of requirements for proposed microgravity hardware facilities and then assist in reviewing results of any design study or advanced technology development activity.

e. Identify any new advanced technology development or payload facilities needed to conduct ground or flight investigations.

f. Identify new areas of scientific research and help promote proposals for microgravity experiments.

g. Establish overall experiment strategies, help review readiness of hardware for proposed microgravity studies.

h. Exchange information with other MPS working groups and invite representatives of these other working groups to attend meetings.

i. Recommend new members invite these new people to meetings and serve as a forum for exchange of ideas and research activities by periodically having all participants give presentations.

When experiments are mature enough to be considered for a specific flight, an investigators' working group is established per standard NASA guidelines. This group, which may include investigators from disciplines outside of MPS, meets and interacts with the original SWG as appropriate.

The membership consists of NASA employees, contractor personnel, NASA-funded investigators, and a strong representation of non-NASA-sponsored investigators from industry. The latter are necessary to ensure that industrial interests are coupled to MPS objectives. The members generally are selected by the chairperson of the group and NASA.

C. International Activities in MPS

The relationships between the U.S. and other nations in MPS are based on the desire to cooperatively generate new science and to share limited future mission opportunities. Since the interests and capabilities of other programs are substantially different from one nation to the other, then the nature of the cooperation varies with each. To date, West German experiments have been carried on Apollo-Soyuz for Professor Hannig of the Max Planck Institute; on Space Processing Applications Rocket (SPAR) I for Dr. Heye, University of Clausthal; on SPAR II for Professor Lohberg of the University of Berlin; and a French experiment flew on SPAR IX for Professor Potard of Grenoble.

Cooperative ground-based research is underway with Dr. Y. Malmejac, Grenoble, France, on the dynamics of metal alloy solidification. A joint program has been established to confirm experimentally certain fluid and interface instabilities due to gravitationally-induced convection. These convection effects had been predicted theoretically by U.S. workers at the National Bureau of Standards (NBS). Currently, cooperative work is underway at the Massachusetts Institute of Technology (MIT) and space experiments are being planned with French hardware accommodated in U.S. facilities in the Shuttle. Furthermore, sharing of space mission opportunities is planned with the Germans who are developing small self-contained packages, Materialwissenschaftliche Autonome Experimente Unter Schwerelosigkeit (MAUS), for the Shuttle which will fly with similar U.S. experiments, Materials Experiment Assembly (MEA), on both German-funded and U.S.-funded missions. Similar sharing of spaceflight opportunities will be explored for other hardware elements on future missions.

In general, foreign use of U.S. developed facilities is possible through proposals submitted and selected in response to an AO. Under these cooperative arrangements, the investigator's government sponsors the research and the U.S. funds the flight operation. An example is a blood rheology experiment being developed by Dr. Dintenfass of the University of Sidney, Australia.

MPS VARIOUS WORKING GROUPS

MAIN FUNCTIONAL RESPONSIBILITY	WORKING GROUPS		
	DISCIPLINE	SCIENCE	INVESTIGATOR
SCIENCE	IDENTIFY NEW AREAS AND CONCEPTS	ESTABLISH EXPERIMENT STRATEGIES TEST NEW EXPERIMENT CONCEPTS	REVIEW FLIGHT READINESS OF SCIENCE PERFORM PRE-FLIGHT AND POST-FLIGHT ANALYSES
HARDWARE	NO FUNCTION	IDENTIFY LONG-RANGE PLANNING NEEDS PROVIDE REQUIREMENTS FOR CONCEPTUAL DEFINITIONS IDENTIFY TECHNOLOGY DEVELOPMENT NEEDS	PERFORM GCEL TESTS ASSIST IN HARDWARE DEVELOPMENT & TESTING ASSIST IN HARDWARE REFLIGHT REFURBISHMENTS & MODIFICATIONS
MISSION	NO FUNCTION	REVIEW PROGRESS OF CURRENT EXPERIMENT PROGRAM EXAMINE OVERALL MISSION CONFIGURATIONS SUPPLY STRAWMAN REQUIREMENTS FOR DEFINITION ACTIVITIES	IDENTIFY SPECIFIC MISSION REQUIREMENTS TRAIN PAYLOAD SPECIALISTS AND ASSIST IN OPERATIONS

FIGURE 8.

The joint development and use of hardware elements alone is not encouraged because of the high technical and financial risks associated with typical materials processing hardware. These risks make it mandatory to define hardware on the basis of well-understood requirements from the ground-based research program.

The German program is actively pursuing space experiments through the European Space Agency (ESA) Spacelab-1 Materials Science Double Rack. In addition, an ongoing sounding rocket program, Technologische Experimente Unter Schwerelosigkeit (TEXUS), provides a limited low-gravity experiment capability similar to the U.S. SPAR program. Simple packages of payload elements (MAUS) have been accommodated for flight in the Shuttle in a manner analogous to the U.S. MEA. In fact, these elements will fly together in 1983 on a pallet in the cargo bay. The Germans have also deposited earnest money for a completely reimbursable Shuttle/Spacelab flight in 1984 on which many industrial experiments will be performed. Industrial interest has been stimulated by initial government investments in silicon crystal growth and turbine blade unidirectional solidification. More recent interest in the chemical processing of unidentified products has occurred. SWG's have been established to coordinate disciplinary activities in semiconductors, metals and fluids.

The French program also includes experiments on Spacelab-1 in crystal growth with some follow-on planned for Spacelab-3. French crystal growth and solidification experiments also fly on Salyut-6, the NASA sounding rocket program, and are planned for future NASA missions as mentioned previously. In general, the French effort is smaller and more research directed than the German activities. No industrial involvement has been identified for reasons that are similar to the U.S. situation.

Other European countries with interests in MPS are Italy, Spain, Great Britian, Denmark, Sweden and Norway. The experiments from these countries center around basic fluid dynamics experiments in the fluid physics module (Spacelab-1) and small scale demonstration experiments in crystal growth and solidification. Interest at this time is strictly academic in nature with a deeper understanding of the processes being the main goal.

Minor interest and inquiries have been expressed by workers in Brazil and Canada. However, no formal activities have been planned at this time.

Other independent foreign programs with MPS interests are those of the Soviets, the ESA member nations, and Japan. The Soviets have been flying space experiments routinely on the Salyut-6 laboratory since the summer of 1978. During an initial 14-week period, about 40 different materials were prepared and teturned to Earth for analysis. These specimens were processed in two furnace systems, SPLAV and KRISTAL, which were designed to a standard set of requirements common to existing terrestrial furnaces. Subsequently, some 20 to 30

additional specimens have been processed, many for Soviet block countries and France. About a dozen of these materials have been reported in the open scientific literature and have included semiconductor crystals, amorphous chalcogenides, oxide glasses, and metal alloys. Most space processing research is carried out at the Space Processing Institute in Moscow where about 300 workers plan, implement and analyze space experiments.

Japan is developing an interest in MPS that parallels German and U.S. activities. An AO to participate in space experiments has been circulated in Japan and the results are being evaluated. Also, the Japanese are planning to purchase a dedicated Shuttle/Spacelab mission in 1986 and are actively seeking collaborative support from other countries. Although there has been no feedback yet, it is not anticipated that there will be substantial industrial commitment at this time until precursor experiments have been performed and a knowledge base established.

For the U.S., the real challenge in establishing relationships with foreign programs is the conflict that arises through the desire to cooperate in the evolution of the underpinning science and the competition that arises through the anticipated commercial application of the knowledge derived. The U.S. has traditionally been a leader in developing new science and technology but has not been as successful in its efficient transfer to new goods and services in the marketplace. Recognizing this concern, NASA has arranged for early industrial participation in MPS through no-exchange-of-fund arrangements which allow intellectual property to be protected. However, in performing industrial experiments, assurance must be provided that full protection is available for such information. One such restriction is the inability to schedule cooperative NASA/industrial experiments in the Shuttle together with cooperative NASA/foreign nation experiments, since the latter require full information sharing by current NASA policies. Foreign industrial experiments are flown as fully cost reimbursable payloads (by the responsible government) and so are not subject to the requirement for information disclosure.

III. FUTURE POTENTIAL OF MPS

A. Scope of the Program

Only those aspects of materials processing that combine deleterious effects due to a sensitivity to gravitational force and potential economic feasibility are of interest at this time. The technical aspects of low gravity that are of interest to industrial and scientific materials processing are:

1. Reduction of sedimentation and buoyancy to enable control of multiphase systems and the preparation of variable density solids.

2. Reduction of density gradient-driven convection (such as thermal and solutal convection) to enable direct assessment of the convection effects experienced in industry and research on Earth in crystal growth, solidification, chemical, and biological separation processes, and the subsequent preparation of materials with more control over structure, composition and external surface features.

3. Reduction of hydrostatic deformation in liquids and semisolids enhance industrial and research activities such as floating zones, crystal growth, and solidification, study of critical point phenomena, preparation of high molecular weight crystals, and diffusion of glasses at temperature above the softening temperature.

4. Development of containerless methods for positioning, measuring, preparing and forming molten, reactive materials.

B. Terrestrial Payoffs From MPS Research and Develoment

In general, the MPS program is interested in studies of process parameters to enhance process control and productivity in Earth processing, in the preparation of limited quantities of precursor materials to provide baseline or reference data, and in the development of methods unique to the space environment by which materials can be prepared which are not possible on Earth. All these interests rely upon the range of process parameters being extended through the reduction of gravity. For example, electromagnetic levitation of some molten metals is possible on Earth; however, in space where heating and levitation can be decoupled, any molten conductive sample can be positioned and heated electromagnetically over a wide range of temperatures. In a second example, glass shells for fusion targets are currently produced up to several hundred micron size in drop towers (free-fall); scale-up to 7 to 10 mm (the projected optimum diameter) may be more easily accomplished in Earth orbit where longer times are possible at high temperature. In a third example, growth of solid-solutal crystals required a combination of high temperature gradients at the growth interface, but low interface migration velocities that are impossible to achieve because of the thermal and solutal convection effects; growth rates and temperature gradients can be decoupled in low gravity, thus, extending the range of stable growth parameters. In all these examples, the first priority is to develop an understanding of the gravitational limitations and to develop theoretical models for one-g and

zero-g behavior, followed by breadboarding simple hardware and acquiring preliminary data before committing to major hardware activities. The emphasis is on the information developed from these experiments being a significant contribution to our body of knowledge in materials processing and the technology transfusable to the private sector. The best measure of these activities is the number of technical papers published in the scientific literature. As of August 1980, from 61 investigations active at that time, 106 technical papers were generated over a two-year period. Also, there was much industrial interest. The publication rate is probably comparable to that of similar National Science Foundation (NSF) funded work, but no attempt was made to develop comparisons. Detailed science reviews of the progress in each investigation are carried out on (roughly) an annual basis by a peer group of non-NASA scientists who write anonymous reports. These reports are aggregated and synopsized by the program scientists and fed back to the PI's. This peer review process complements the initial proposal review which is done by mail in the same manner used by NSF. The industrial interest is evidenced by the ground-based investigations by private industry, IGI participation on selected investigations and the growing interest in joint NASA/industry space processingventures. Several such arrangements have been established through the Commercial Applications Office at MSFC. Other less formal industrial liaisons have been established through academic institutions such as the Materials Processing Center at MIT.

The following list of priorities represents the thrust of the MPS program and its relation to typical areas of private and public center interest:

1. Crystal Growth Processes

a. Melt growth is the most widely used technique for production of high technology, single-crystal materials for semiconductor chips used in large scale integrated circuits for communications and computers. The MPS program emphasis is concentrated on achieving chemical homogeneity, hence, maximum electrical performance, in HgCdTe and lead-tin-telluride (PbSnTe) semiconductors. These crystals are among the most sensitive and important infrared sensors and most difficult to grow materials on Earth. The two materials bridge the spectrum of growth conditions. In the case of PbSnTe, one component is less dense than the bulk melt, hence the system is subject to solute instabilities. The HgCdTe, on the other hand, has the opposite problem. One component is more dense than the bulk melt. Therefore, it is subject to solidifying interface-shape instabilities. Low-g experiments will determine how well such systems can be grown in the absence of gravity. These are two examples of several commercially valuable crystals whose properties may be enhanced by melt growth in a low-g environment.

b. Float zone growth is a variation of melt growth in which the material can be melted without the deleterious contact with any container wall. Floating zone techniques are widely used to produce crystals such as doped silicon for semiconductors and solar cells. While large, efficient crystals are grown commercially with this process, gravity does limit the size and type of crystals

that can be grown and does introduce growth rate fluctuations that cause chemical inhomogeneities that necessitate cutting the crystal into small chips for high performance applications. The MPS program emphasis is on establishing uniform growth conditions in commercially important materials such as indium-doped silicon and CdTe which is a semiconductor with a very high theoretical maximum energy conversion efficiency.

c. Solution growth is an important alternative to melt growth for materials that are unstable at their melting point because the crystals can be processed at much lower temperatures. The MPS program emphasis is directed toward triglycine sulphate (TGS) a room temperature, infrared detector material and gallium-arsenide (GaAs) one of the most important semiconductors for a wide range of applications from microwave devices, to computers, and solid state lasers. TGS is grown from a transparent, water base solution that permits observation of the growth process; furthermore, the infrared detectivity of the currently available material is constrained to about 20 percent of the theoretical limit because of gravity influenced growth defects. Thus, this system represents a good model material that is well characterized and has the possibility of a technological breakthrough if substantial improvement can be realized.

GaAs is one of the most important semiconductors with uses ranging from microwave devices to solid state lasers. It can be readily grown in bulk form but with considerable imperfections. Usually, in device fabrication, a thin film of high quality GaAs with precisely controlled additives is grown by liquid-phase epitaxy (layered growth) over a bulk melt grown crystal substrate. However, two problems arise. First, in the growth of the epitaxial layer, the solvent is less dense that the Ga/GaAs solution. Therefore, the growth system cannot be stablized against convection. Second, it is very difficult to control the saturation at the growth interface by lowering the temperature of the substrate.

Although it is possible to bury the defects in the substrate, the buried defects tend to migrate with time and eventually emerge at the surface, causing premature device degradation or failure. Therefore, for certain applications, it would be highly desirable to have better substrate material. For these reasons the growth of GaAs in low-g is of interest from a theoretical as well as a technological point of view.

d. Vapor growth does not compete favorably with other growth techniques on Earth where large crystals are required because gravity disrupts the vapor transport mechanisms; it is a useful process for growing "whiskers" or thin monocrystalline films and for materials that do not lend themselves to other convenient techniques. The absence of gravity opens new possibilities for the growth of large, flat, pure crystals by the vapor technique; therefore, the MPS program includes the investigation of HgI_2 nuclear detector crystals and HgCdTe and copper-indium-antimony (CuInSb) solid solution semiconductor crystals.

HgI_2 which is an excellent prospect for nuclear radiation detector that can be used at ambient temperature. One of the factors that is believed to limit the performance of this material is its high density and extreme weakness at the growth temperature. Because the crystal has a layer structure, self-deformation during growth under one-g is believed to be an important factor in producing dislocations which degrade the performance as a nuclear energy detec tor. The growth of such a crystal in low-g could eliminate such strains at the growth temperature. It is also anticipated that the perfection of the crystal might benefit from the more quiescent growth conditions expected in space. The solid solution semiconductor materials are being pursued not only because of interest noted earlier in the materials, but also because earlier flight experiments indicated much higher growth rates in zero-g than those produced on Earth.

2. Solidification Processes

Directional solidification is a casting process used to produce single crystals and two-phase composite materials wherein the microstructure is aligned in a particular direction such that the mechanical and physical properties differ along various axes, or wherein fine, homogeneous dispersions are achieved. Common examples of two- (or multi) phase composites might be fiberglass wherein glass filaments are suspended (either unidirectionally or randomly) in a plastic matrix to increase strength and provide anisotropic properties and dispersion hardened steel wherein small carbide particles are included in the steel matrix to improve strength. The advantage of this process is that the growth rate and, hence, the microstructure and properties can be controlled. zero-g, the tendencies for the second-phase materials, to be uncontrollably mixed through convection or separated by sedimentation/buoyancy, are eliminated and sharper thermal gradients and lower growth rates are achievable. The MPS interest in directionally aligned composites is built upon the extraordinarily high magnetic coercivity measured in space-grown composites of Mn-Bi/Bi. Additional interest is based on the potential of approaching the theoretical maximum magnetic strength of materials such as samarium-cobalt ($SmCo_5$) which is 10 times higher than currently realized on Earth.

The second aspect of directional solidification finds application in miscibility gap alloys that defy preparation in one-g in bulk quantities because gravity-driven effects cause the materials to segregate upon solidification. There are some 500 such combinations of materials that have a liquid phase miscibility gap. If producible, such materials might have such diverse applications as electrical contacts (as replacements for silver and gold) and self-lubricating bearings. Experiments in low-g have successfully produced finely dispersed, homogeneous mixtures of Ga-Bi and Al-In. Other materials, such as Cu-Pb, Cd-Ga, Ag-Ni, Al-In-Sn, Cu-Pb-Al, Cd-Ga-Al, and transparent model materials, are being studied in the MPS to define nongravity segregation phenomena and to establish the techniques to produce these unique materials for property evaluation. While applications may be speculated from theoretical considerations, the inability to produce bulk quantities on Earth necessitates the making of samples in one-g to verify those expectations and the application viability.

Undercooled solidification is the rapid quenching of molten materials at temperatures well below their freezing points. This process is valuable in the preparation of amorphous (glass or glass-like) materials as well as pure single crystal and metastable phases. Materials have a natural tendency to form uniform crystalline structures; therefore, to make a glassy material, the atoms must be "frozen" in a random order before the crystalline state is achieved. The common glass materials can be chilled and solidified by common Earth-based techniques. Other materials can be solidified in the amorphous state, except that the atomic mobility is generally so rapid that heat (especially for molten materials that must be held in a crucible) cannot be extracted before crystal nucleation takes place. Through elimination of the gravitational requirement for a container, a vast array of materials can be processed in the amorphous state in low-g, thus, extending the materials properties available to mechanical and optical designers. The so-called "reluctant glass forming" materials are the basis of the MPS program effort. NASA is doing and sponsoring work on glasses such as CaO-GaO to produce such materials in bulk quantities and to confirm their improved energy transfer efficiency for applications such as laser hosts. The NASA MPS program has developed unique ground-based free fall facilities at MSFC in which extreme undercooling (hundreds of degrees centigrade in excess of existent theory) has been achieved in the production of bulk quantities of pure single crystals and superconducting metastable phases; these materials have not been made in bulk quantities by other methods. The emphasis in undercooled solidification centers on the formation of pure Nb and the superconducting phase Nb_3Ge, which has a high superconducting transition temperature (23.2°K) and offers great promise for electrical transmission and electrical devices. By producing these compounds in samples large enough to be analyzed by neutron diffraction, the relationship between perfection of the crystalline structures and the superconducting performance can be analyzed. Such studies may shed some light on methods for obtaining superconductors which work at higher temperatures.

Casting technology has already been advanced through zero-g experiments that unequivocally illustrate how the crystalline structure grows and is subsequently disrupted by gravitational effects leading to the pervasive occurrence of property variations from top to bottom of a casting (an engine block, for example) and shrinkage. Castings made in zero-g have uniform microstructure and properties. Therefore, the MPS program is using the zero-g environment to study the formation and resultant properties of various cast materials (both simple model materials and commercial alloys) to establish process controls and techniques that might be adapted on Earth. Furthermore, NASA is studying the prospects of casting complex, single crystal shapes (such as turbine blades) in space to achieve theoretical maximum properties from the materials.

3. Containerless Processing

Levitation technology is being pursued to develop devices for positioning, melting, manipulating, and resolidifying materials in space without the constraint of containers or crucibles. In space, liquid materials will remain in a stable, spherical drop without containers; thus, small restraining forces are sufficient to keep the drop where desired. The processing of materials without the

necessity of containers is an exciting and unique capability of the space environment and permits the formation of pure materials without contamination from the container, permits the formation of amorphous (glass) materials that cannot be made on Earth, and permits the measurement of physical properties of molten materials at temperatures that exceed the melting point of crucibles needed on Earth. The MPS program technology is directed toward the development of high temperature acoustic levitators (or positioning devices) for use with materials that can be processed in a gaseous environment, electromagnetic levitators for use with electrically conductive materials, in either gaseous or vacuum processing environments, and electrostatic levitators for use with dielectric materials that need to be processed in vacuum environments. Low-g flight experiments have been conducted successfully with both acoustic and electromagnetic devices, and the practical application of this technology to a vast spectrum of both scientific and commercial processes can be realized through the elimination of detrimental gravitational effects.

4. Biological Separation Processes

Bioseparation technology is being addressed because Earth-based techniques for producing high purity materials in significant quantities from complex biological mixtures are adversely affected by gravity. In the gravity-free environment of space, separation techniques that are based on electric fields and biological material surface characteristics become highly efficient. Furthermore, such separation techniques are inherently gentle and do not damage or destroy live cells or other material. The focus of the MPS program is in developing the technology for separation techniques such as electrophoresis, isoelectric focusing, and phase partitioning. Substantive advances have already been made in the improvement of the Earth-based technology through the MPS program, and a venture by a private sector firm has been formalized to explore the viability of commercialization of pharmaceuticals separated by such techniques in space.

5. Fluids Mechanics and Chemical Processes

Fluid mechanics are critical to nearly all material processes since at some point in the process, the materials exist in either the liquid or gaseous state and are, therefore, subject to gravitational disturbances. The MPS program has undertaken to analyze the processes and to develop appropriate theoretical and mathematical models for both the one-g and low-g aspects once such understanding is imperative to understanding the Earth-based property limits and the viability of low-g experimentation. The development of adequate mathematical models (at least for simple materials) is especially important since many, if not most, commercial material processes have been developed empirically over long periods of time (dating as far back as the Bronze Age) and often involve such complex mixtures and combinations of materials that they defy analysis of the reactions and interactions taking place. Low-g offers an opportunity to isolate one of the major variables in understanding these processes.

Chemical processes are being studied to elucidate the effects of gravity in processes where particle size and geometry may affect the chemical reaction kinetics. Currently, the MPS program is investigating the reaction kinetics of polymers to understand and, perhaps, overcome the current commercial size limitations in producing uniform, microscopic particles for applications such as blood cell counter and electron microscopic calibration, calibration of pore sizes in living or other membranes, and for tagging biological materials. Under one-g, as the particle size is increased, they tend to aggregate and sediment. An early low-g flight experiment may provide valuable information on chemical process controls applicable to the field of polymer chemistry.

IV. RELATED SPACE CAPABILITIES

A number of supporting systems have been identified to provide the functional requirements of materials processing experiments. The experiments range from simple models for proof-of-concept to continuously operating pilot plants. First, to support any MPS experiment, there must be a carrier and they range in concept from a drop tower on Earth, to aircraft, sounding rockets, Space Shuttle, Spacelab, free-flying satellites with automated mechanisms, and extraterrestrial apparatus with robotic devices. These carriers must be specifically designed to provide a low-gravity environment, except for the last case, which range in time from four seconds for the drop tower on Earth to many months of unattended operation on a free-flying satellite.

MPS experiments also require large amounts of electrical energy compared to other space ventures, thereby requiring a large electrical power system. However, in the case of metallurgical experiments, the energy is used primarily for heating and melting, so solar furnaces have been proposed for the future. Concomitant with heating goes cooling for quenching, among other purposes, with heat exchange systems requiring fluid transfer. Also measuring systems, including data communications with controllers on Earth, are necessary to manage the experiment or manufacturing facility. Finally, automated mechanisms will be required ranging up to complicated robotics which can perform a number of mechanical functions under microprocessor control.

A. Ground-Based Facilities

As an economical simulation technique, ground-based facilities, namely drop tubes and drop towers, have been developed to provide low-cost, functionally flexible and readily available low-g test facilities. MSFC operates two drop tubes (one of 100-foot length and one of 300-foot length) and a 300-foot drop tower. These facilities provide between two and four seconds of low-g time. In the drop tubes, molten droplets are released into an evacuated tube and are solidified during the vertical free fall. The drop tower employs a free-falling aerodynamic container within which experiment packages are mounted for zero-g tests.

B. Aircraft Experiment

By flying parabolic trajectories, short periods of low gravity can be achieved with aircraft. The NASA/Johnson Space Center KC-135 aircraft has been used for several years to obtain low-g material science data and equipment verification. This aircraft can accommodate a relatively large experiment package which may be either automated or manually operated; the KC-135 low-g operating periods are, typically, 15 to 30 seconds and are

quite satisfactory for solidification studies and precursory experiments in other areas, such as containerless processing. More recently, the NASA/Dryden Flight Research Center F-104 aircraft has been used for MPS precursory experiments. This aircraft accommodates small, automated experiments and can achieve 30 to 60 seconds of microgravity time.

C. Sounding Rocket Experiment

MSFC has, for several years, employed sounding rockets to provide a number of short-duration (4 to 6 minutes) flight opportunities for investigators to pursue their research in low-gravity phenomena and to develop concepts and techniques to be used later in Shuttle flights.

The low-gravity environment on sounding rockets was found to be an excellent interim tool for meaningful research in materials science. However, the short duration and harsh launch environment, including spin-up and spin-down, provide a real challenge for experiment design. Despite these limitations, the sounding rocket program has been beneficial for accommodating a cadre of experimentalists interested in conducting materials research under low-gravity conditions. The scientific goals have been worthy and many of the research ideas to be carried out on the Shuttle emerged from these experiments. Considerable experience has been gained in developing and testing new hardware, and a significant inventory of off-the-shelf hardware has been built up that can also be used to conduct longer duration experiments which will be flown on a space-available basis during Shuttle operations. Experience in developing low cost hardware and experiments has been a vital product of this program. The sounding rocket is expected to continue to be an important experimental capability in the MPS program for several years.

D. Space Shuttle

The Space Shuttle is a transportation facility or carrier providing space environmental capability for several kinds of experiment packages for nominal periods of time of, initially, five days. Experimental facilities to be carried on the Shuttle include: self-contained packages on the Orbiter middeck, MEA, Spacelab module, and Spacelab pallet (Figures 9 through 12, respectively). Also, the Shuttle is the means of putting a free flyer such as the Materials Experiment Carrier (Figure 13) into orbit and resupplying it.

E. Future Payload Requirements

Physical and engineering requirements for scientific/commercial candidate payloads were determined, largely on the basis of interviews with materials experts from government, industry and university laboratories, including members of the NASA MPS working groups and other PI's of NASA-sponsored MPS research.

FIGURE 9

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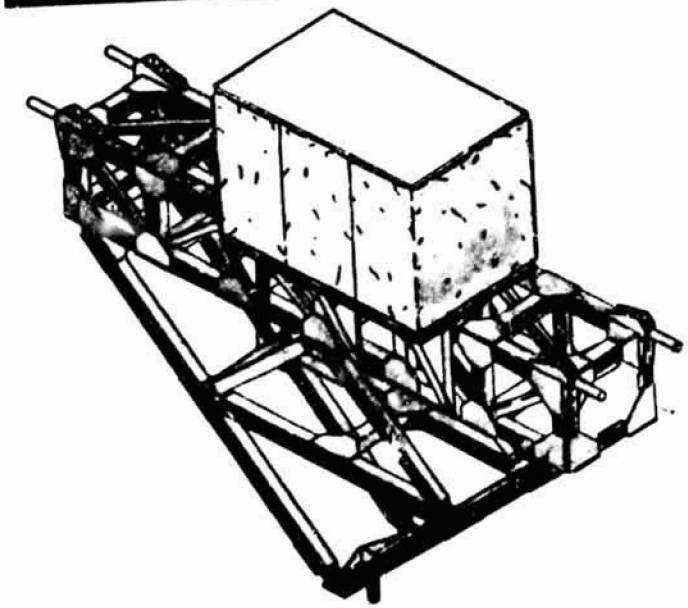
MATERIALS EXPERIMENTS ASSEMBLY [MEA]

MEA ON MPE SUPPORT STRUCTURE



MEA ON PALLET

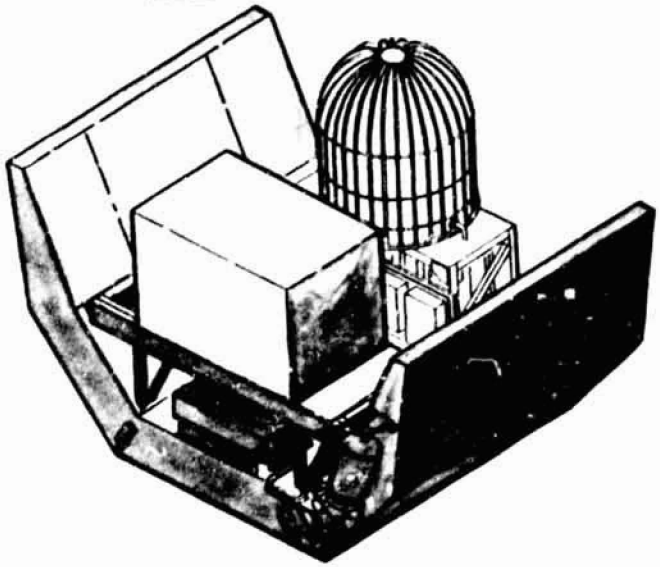


FIGURE 10

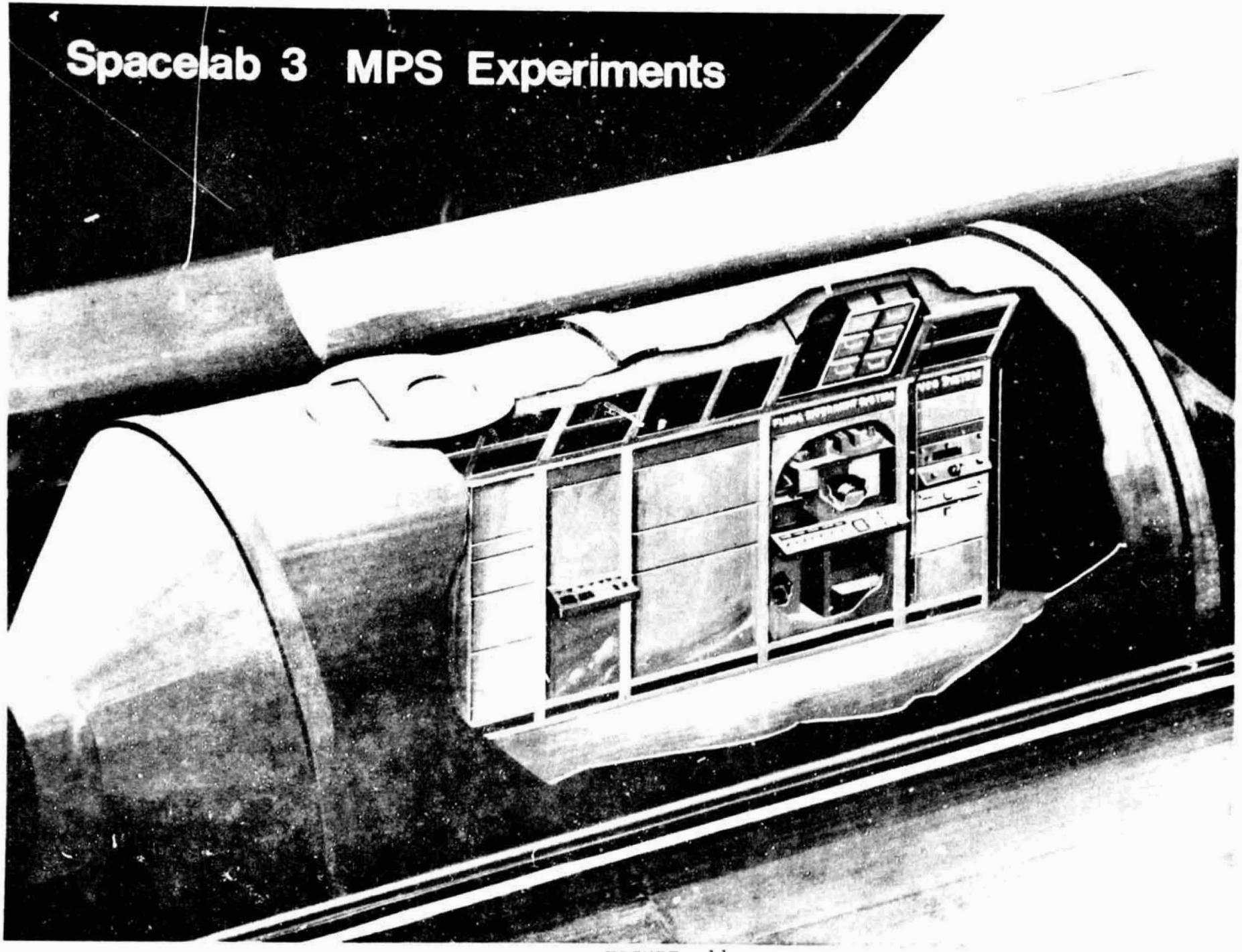
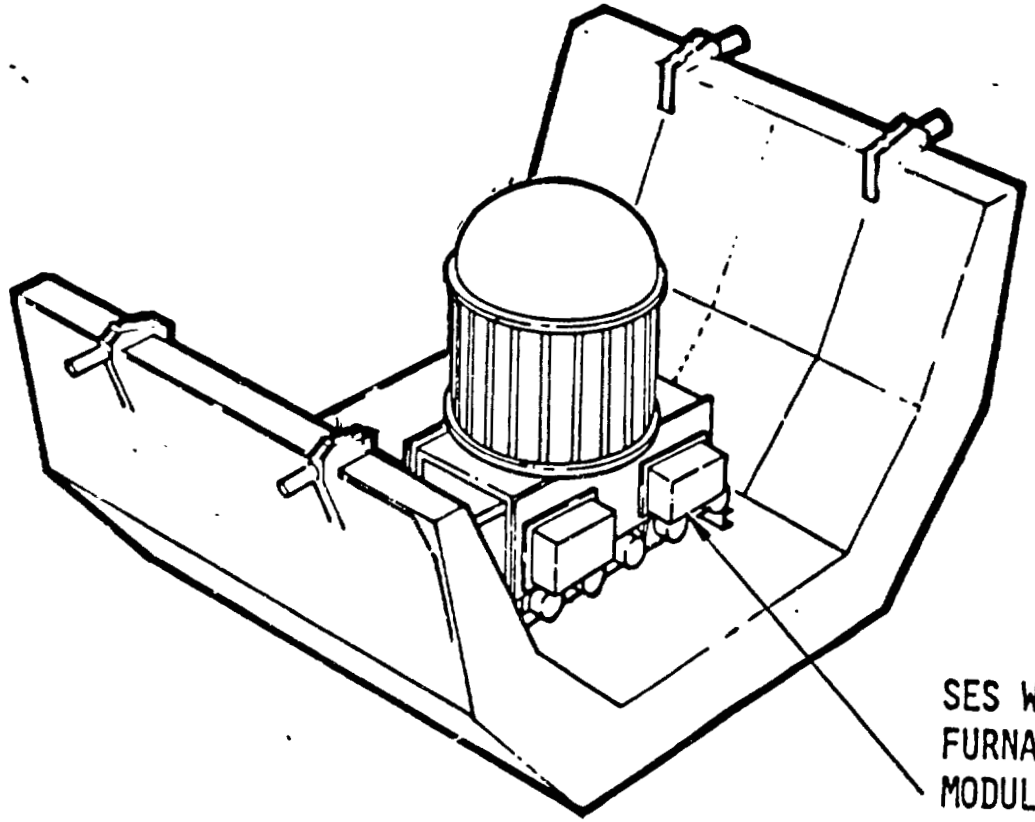


FIGURE 11

SES/PALLET INSTALLATION



SES WITH
FURNACE
MODULE
(SHOWN WITHOUT
THERMAL INSULATION
FOR CLARITY)

FIGURE 12

MATERIALS EXPERIMENT CARRIER (MEC)

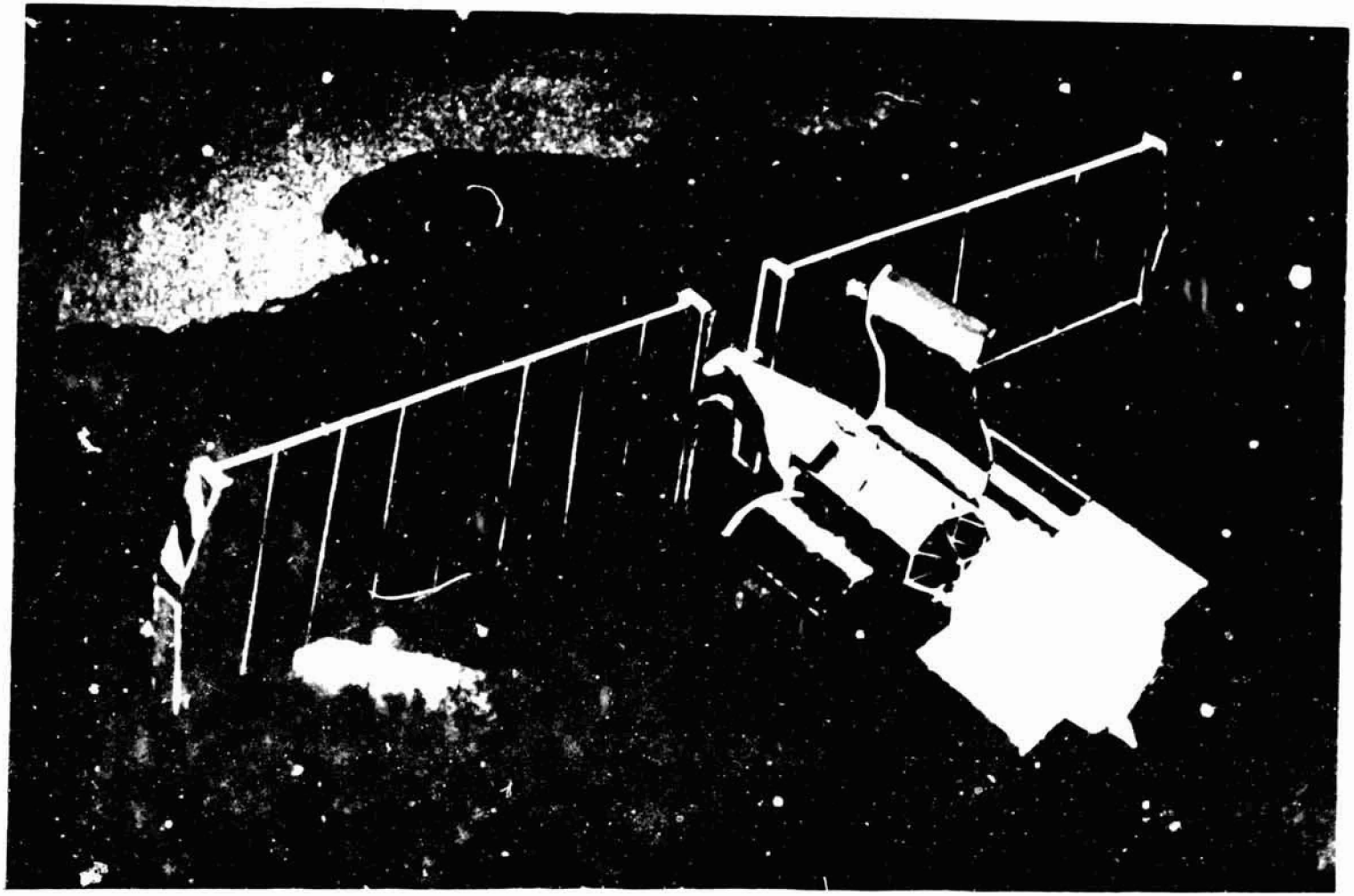


FIGURE 13

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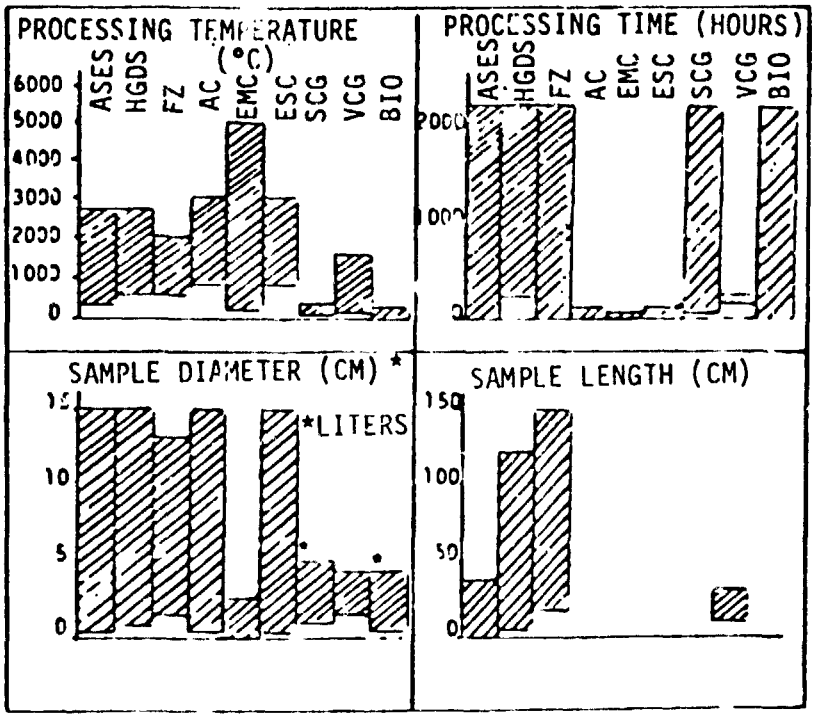
Review of past and current MPS projects and contacts with potential scientific and commercial users led to a grouping of MPS materials processing methods. From these groups, sufficient interest was found in the following nine processes to provide a high probability of their becoming future payloads, so they were the ones considered in developing payload requirements.

- o ASES - Advanced Solidification Experiment System
- o HGDS - High Gradient Directional Solidification
- o FZ - Float Zone
- o AC - Acoustic Containerless Processing System
- o EMC - Electromagnetic Containerless Processing System.
- o ESC - Electrostatic Containerless Processing System
- o SCG - Solution Crystal Growth System
- o VCG - Vapor Crystal Growth System
- o BIO - Bioseparation System

Composite processing requirements for candidate payloads are plotted in bar chart form (Figure 14). The key parameters shown are temperature, time, sample diameter, and sample length. The multidiscipline character of MPS experiments to be accommodated is reflected in the wide range of processing parameters indicated in the chart.

Composite payload requirements of weight, volume, power and energy are plotted in Figure 15. A standard payload envelope was defined as an engineering compromise to accommodate all of the MPS payload research objectives and commercial demonstrations.

It became clear from these studies that economy of spacecraft operations for materials processing ultimately requires a free-flying satellite. This automatic, unattended free flyer will provide the long duration at low-g needed for continuous processing, such as free-flow separation of pharmaceutical products, repetitive operations, such as growing a large number of semiconductor crystals for infrared sensors. The Space Shuttle can serve as the transportation vehicle to place the free flyer into orbit, to supply it with raw material to pick up the finished product. This requires teleoperator manipulation and maneuvering of raw material and product packages.



Payload Notation

ASES - Advanced Solidification Experiment System
HGDS - High Gradient Directional Solidification
FZ - Float Zone
AC - Acoustic Containerless
EMC - Electromagnetic Containerless
ESC - Electrostatic Containerless
SCG - Solution Crystal Growth
VCG - Vapor Crystal Growth
BIO - Bioprocessing

FIGURE 14. COMPOSITE PROCESS REQUIREMENTS

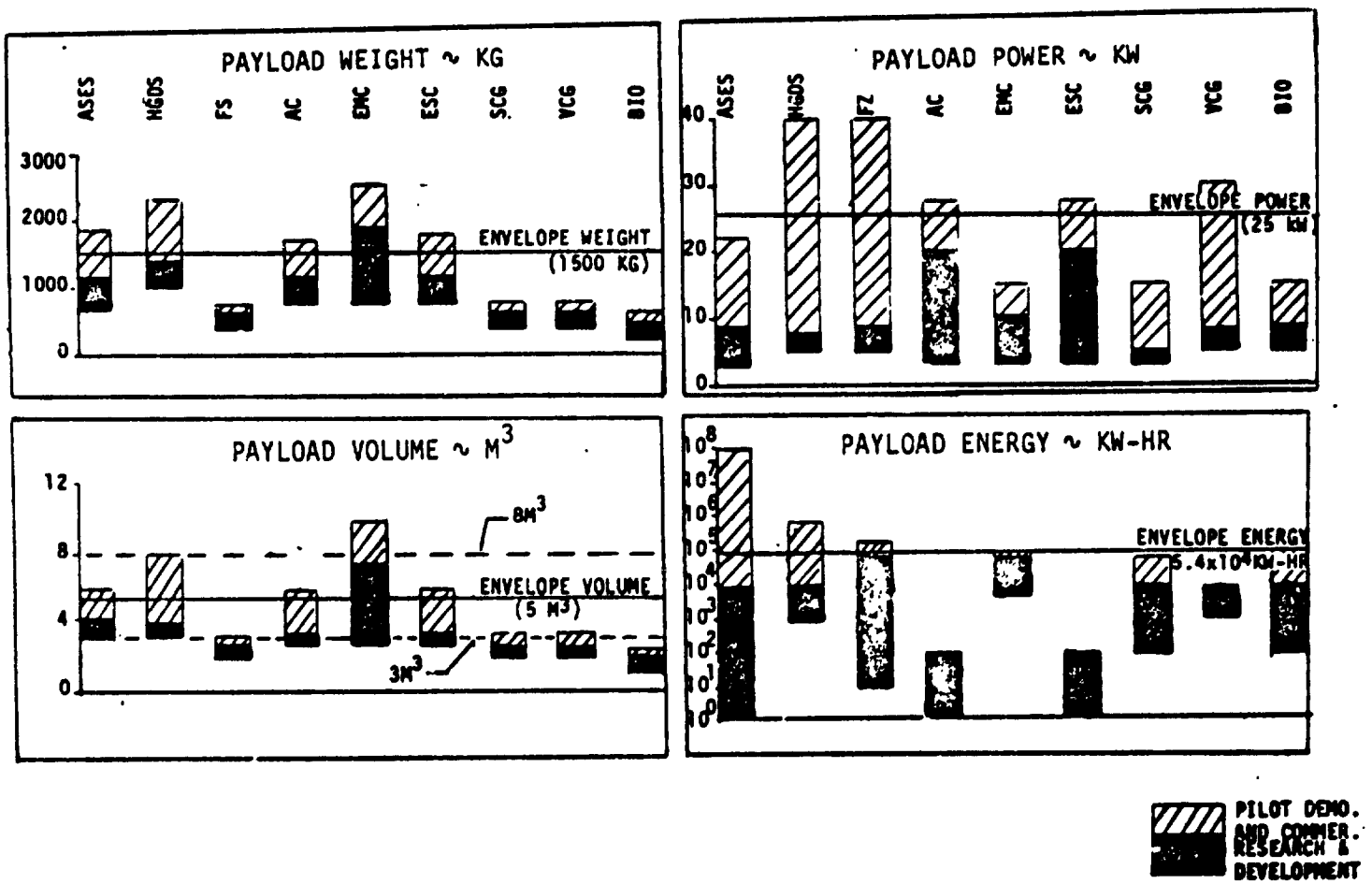


FIGURE 15. COMPOSITE REQUIREMENTS ON MEC

Also, it became clear from these studies that high levels of electrical energy will be needed to do materials processing for commercial development. An early example of this need has been defined by MDAC for its commercial development of a separation facility for pharmaceutical materials in space. A free-flyer capability will be required according to MDAC in the mid-1980's and, therefore, it is an integral and necessary part of the MPS program planning.

F. Extraterrestrial Space Materials Processing

The application of the low-g research to terrestrial materials production is a primary goal of the MPS program, as is the use of space processing of materials when transportation and processing is both technically and economically practical. There remains the ultimate step of processing materials indigenous to space--in space--for space applications. The in-situ mining, processing, and fabrication of materials entail exciting long-term prospects as well as near-term challenges in research and technology to estbalish the feasibility and practicality. Not only is it necessary to develop a unique "space chemistry" applicable to lunar, planetary, or asteroidal materials, it is necessary to develop a commensurate automation and robotic technology to establish feasibility and to facilitate eventual implementation. The beginning of this long range effort is discussed in Section II.

In terms of space capabilities planned or available to do extraterrestrial space materials processing, there is a base set of tools with which to start the develoment of necessary technology. These include microprocessor-controlled robots used in some manufacturing operations today (such as welding); teleoperator maneuvering devices for exchanging boxes and samples in furnaces; and manipulators such as those used on planetary landers for digging and analyzing soil samples. These need to be developed further to be larger, more flexible and independent. Additionally, there is a need to further develop early versions of reduction cells to make aluminum, silicon and other intermediates from extraterrestrial soils, followed by apparatus for unattended extrusion of sheets and shapes, deposition of coatings, automatic cutting, stamping, brazing, welding and assembly of components. For instance, it has been proposed that a space built, solar power station may be needed to supply electrical energy to Earth and that the large volume of solar cells, collectors and supporting structures might be built less expensively in space. This is the challenge of extraterrestrial MPS.

V. PROGRAM OPTIONS

The MPS program is structured on goals, objectives, and priorities to provide the rationale for selecting the implementing tasks and flight plans. These plans ultimately derive the needed budgetary resources to accomplish the goals. They support a certain number of researchers, including in-house NASA, academic and industrial, in addition to the payload development (flight hardware) contractors and flight operations.

There are a number of options for the budget, ranging from (1) going out of business on the part of the government, through (2) the current minimum level program, to (3) an augmented program that will support a practical schedule to demonstrate the opportunities with the least delay.

A decision to withdraw all government leadership and support would leave the field to private industry. Industry would then do the necessary research whenever it was convinced that profits could be realized in the short term or near future with products in its field of interest. This course of action would be an abdication of the charge contained in the National Aeronautics and Space Act of 1958 to transfuse technology to the private sector, since the government controls the way to space and has the most information on operations in space. The shear magnitude of the total systems problem in implementing a space venture is larger than any one company normally is willing to take on, considering a new venture with long-term payoff and high risk. By way of history, it was necessary for the government to lead the way with research and demonstrations in communications satellites, jet-turbine engines for aircraft and nuclear-power reactors, for example, until a profitable threshold was reached. It appears that the same trend is evident in MPS. Also, it should be noted that several foreign governments, who compete openly for high technology markets against American industry, have opted to support MPS.

The current budgetary plan, shown in Table V-1, is considered to be the minimum required to stay in business. It is a profound reduction from previous requests which were based upon viable program plans for development and capitalization new processes. It supports a subcritical number of investigators and flight experimenters categorized in Table V-2. The payloads currently being developed on this budget are the Monodisperse Latex Reactor (MLR), Fluids Experiment System (FES), VCG system, and the Solidification Experiments System (SES). It is expected that the program will be able to grow to provide experimental facilities for a larger cadre of investigators based on the planned expansion in budgetary resources, if allowed. The figures shown include funding for the governmental and academic segments.

TABLE V-1.

MATERIALS PROCESSING IN SPACE
SUMMARY OF CURRENT FUNDING PLAN
OSTA BUDGET SUBMISSION

	FY81(R)	FY82(R)	FY83	FY84	FY85	FY86
AR&DA (SRT)	9.9	14.0	15.3	15.3	23.3	23.3
P/L DEV	7.5	9.0	8.7	8.2	4.6	15.0
EXP OPNS	1.3	4.7	17.6	25.8	36.0	33.7
SPACE MAT SYS	–	–	–	6.0	6.0	6.0
MPS TOTAL	18.7	27.7	41.6	55.2	69.9	78.0

TABLE V-2.
CURRENT INVESTIGATORS IN MPS

Discipline	Ground-Based	Flight Experiments
Crystal Growth & Solidification	16	8
Containerless	7	2
Chemical & Biological	7	1
TOTAL	30	11

A larger but feasible budgetary plan is described in Table V-3, which augments the current program plan to a practical level of effort to realize the potential payoffs. The Applications Research and Data Analysis (AR&DA), Supporting Research and Technology (SRT), budget item is expected to support 70 or more scientific investigations instead of the 41 currently active. The payload development would support the 5 experiment systems listed in the note with Table V-3, and the experiment operations would provide for reflights of the apparatus currently being developed. While the experiment operation items include flight operational support of commercial ventures, they do not include STS charges or the private funding required to provide commercial payloads. The future requirements in the private and international segments cannot be estimated at this time, since we do not know the depth or extent of private plans for involvement. It is expected that commercial payoffs will begin only after several flights of each of the systems listed in the note.

In order for the MPS program to demonstrate feasibility to the commercial/industrial sector, it needs many flight opportunities and experimental payloads such as the systems listed in the note to Table V-3. The MPS program cannot be expected to be fruitful in terms of commercial payoffs until there has been a large number of investigations to address the broad scope of technologies identified. This requires expensive hardware, that is the development of new flight experiment payload systems to accomplish the tasks set forth. Table V-4 shows the steps which must be taken in sequence and, in most disciplines, the MPS program is still in the research stage. The current budget, Table V-1, does not provide for development of the needed payload systems except the first Spacelab complement which includes the FES, VCG system, and SES.

A detailed explanation of the tasks and categories covered under each budgetary line item follows.

The UPN 179, "AR&DA," embraces the sustaining research and technology activities fundamental and necessary to the realization of the MPS program goals. The UPN 179 is structured with the following content:

- Supporting Research and Technology (SRT)

  Crystal Growth Process Research
  Solidification Process Research
  Containerless Processing Research
  Fluid and Chemical Process Research
  Biological Separation Process Research
  Vacuum Processing Research

TABLE V-3.

SUMMARY OF AUGMENTED FUNDING PLAN
FOR A PRACTICAL PROGRAM TO REALIZE PAYOFFS
IN A REASONABLY SHORT TIME

	FY81	FY82	FY83	FY84	FY85	FY86
AR&DA (SRT)	–	–	16.8	20.0	23.3	26.3
P/L DEV*	–	–	26.0	26.1	29.2	32.3
EXPT OPNS	–	–	18.3	25.8	36.0	35.0
SPACE MAT SYS	–	–	–	6.0	6.0	6.0
MPS TOTAL	–	–	61.8	77.9	94.5	99.6

* NOTE:

Payload Development (P/L Dev) includes the following projects. Each payload device is capable of supporting the experiments of many investigators.

1. Floating Zone Experiments System
2. Electromagnetic Containerless Processing Module
3. Bioprocessing Module
4. Materials Experiment Carrier (MEC)
5. Advanced Materials Experiment Assembly

Implementation Of MPS Program Goals

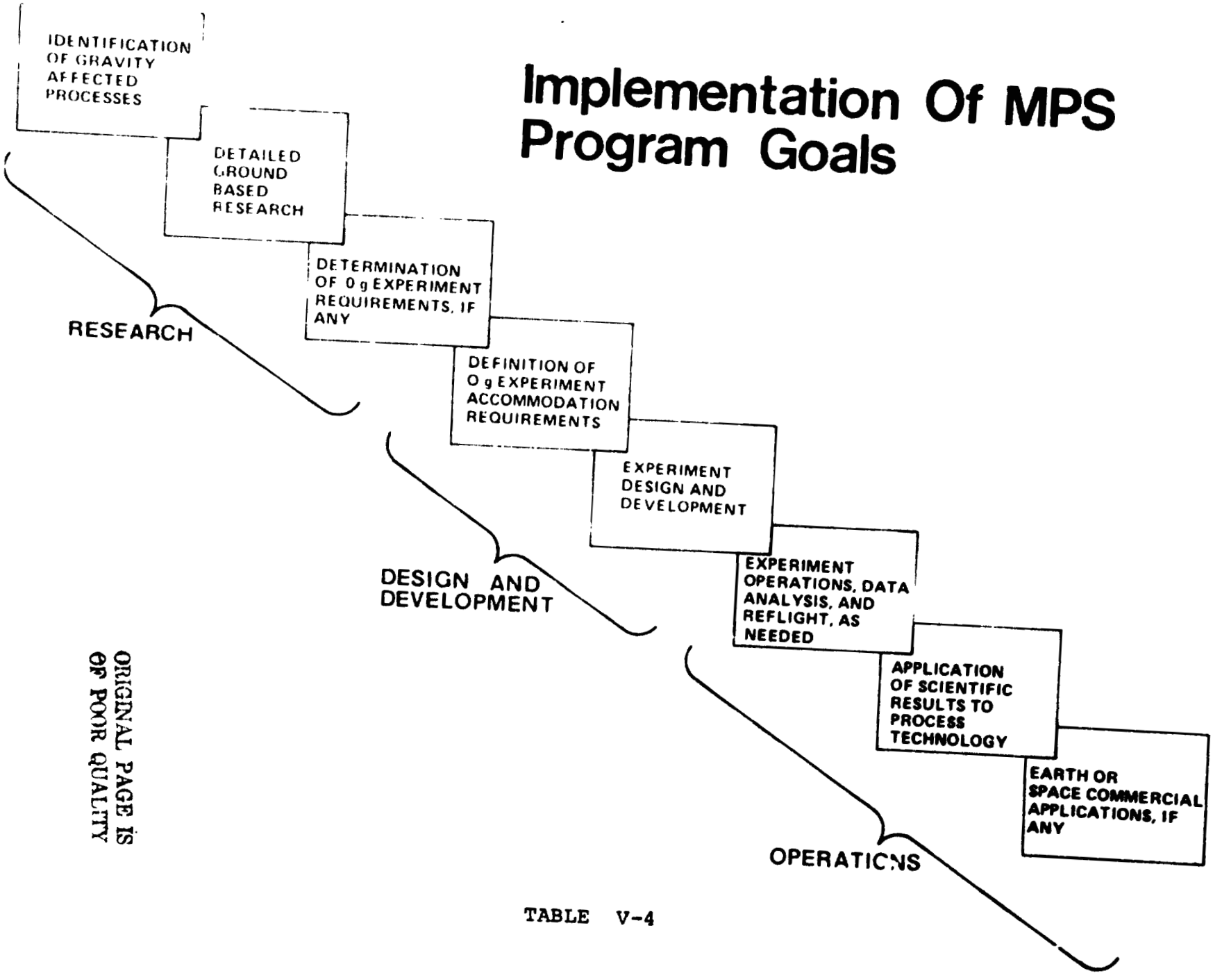


TABLE V-4

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- Advanced Technology Development (ATD)

  Process Technology Development (Including Automation)
  Payload Technology Development
  Low-g Simulation Technology
  Extraterrestrial Materials Processing Technology (Including Machine Intelligence and Robotics)

- MPS Payload Definition Studies

  Phase A and Phase B Studies Consistent with Planned new Activities

The areas of research, Research Technology and Operating Plans (RTOP's), under SRT are intended to be long term, comprehensive programs composed, primarily, of contracted research efforts with PI's whose work has been selected through a peer review process under the AN system. The RTOP's represent areas wherein gravitational forces and/or other elements of the space environment are known and have been demonstrated to have a significant effect upon the process variables, and wherein significant commercial potential exists. The research program in each area is developed to systematically isolate and analyze the process variables essential for applications. The sponsored research is selected within the context of the existing data base in the materials science and processing disciplines, and within the context of work sponsored or anticipated by other sources.

The areas of technology (RTOP's) under ATD are intended to provide the techniques, proof-of-concept, and breadboard activities to permit implementation of the MPS research program through the necessary and incidental payload hardware development efforts. This effort is essential and complementary to the research program in that it will preclude or minimize high programmatic and, possibly, scientific impacts to the hardware development activities. The technology areas are derived from the commonality of design requirements and state-of-the-art advances that permeate through all of the payload hardware developments that have been defined and forecast from the ground-based research. The technology effort is anticipated to be largely based upon contracted study efforts augmented by NASA in-house expertise.

The Phase A and Phase B definition studies are the natural extension of the SRT and ATD through the predevelopment aspects of the NASA-phased project planning philosophy leading to the agency commitment for a new start or new initiative. The definition studies provide the engineering insight and industrial planning base for the hardware procurements.

MPS Shuttle/Spacelab Payload Development - UPN 674

As a necessary and incidental adjunct to the realization of the program goal, spaceflight payloads are needed in which to conduct the research, demonstrations, and preparation of exemplary materials. Subsequent to a well characterized ground-based research program, and appropriate technology and definition studies, and upon commitment of the agency to proceed with new starts or new initiatives, the design, development, and support activities associated with MPS payloads will be accomplished under UPN 674. The payload development activities entail the following:

Payload Design and Development
Payload Integration Support for Initial Mission
Initial Mission Operations Support
PI Experiment Development
PI Experiment Support

Relative to the Shuttle ground operations flow, UPN 674 provides for Prelevel IV integration, and the support to the Level IV-I integration that may be required from the MPS payload developer and the PI's. Level IV-I integration expenses are to be budgeted by the appropriate Mission Management Office commensurate with payload mission assignments from other appropriate fund sources. Real time mission operations support, if required by either the MPS payload developer or the PI's, would be included in UPN 674. Payload specialist training and mission activities are to be funded from other sources through the Mission Management Office, including those specialized activities or training required in conjunction with the PI experiment development. The PI experiment development provides for the analyses, ground-based research, precursory experimentation, ground-control and flight-sample preparation, real time mission support, and post-flight analyses. NASA-sponsored scientific flight experiments are selected through a peer review of responses to an AO; commercial application flight experiments originating from joint endeavors or reimbursable flight opportunities are supported to the extent appropriate under UPN 6xx, "Materials Experiment Operations." PI experiment support is essential to accommodate special analyses, testing, and hardware support unique to the PI's experiment development and implementation. Operations associated with precursory experimentation and with the Ground Control Experiment Laboratory (GCEL), because of their sustaining and generalize support, are funded from UPN 6xx, "Materials Experiment Operations," although the original procurement of GCEL hardware is generally a part of the development contract.

Currently, the MPS payloads to support the Spacelab 3 mission and a shared satellite deployment mission are being developed under UPN 674. Additional Shuttle or Spacelab MPS payload items are required and will be pursued to meet the scientific demands of the various research areas evolving from UPN 179, AR&DA. A free-flying experiment capability is essential for MPS to achieve the

low cost per sample essential for multiple sample research programs and commercial applications, as well as, to achieve long low-g processing times and to satisfy high power, energy, and heat rejection demands. Consistent with the advent of an interim free flyer and/or a power system and the MEC, to be developed by the Office of Space Transportation Systems, supporting payload developments will be pursued under UPN 674.

Materials Experiment Operations - UPN 6xx

Pursuant to NMI 8010.1, "Classification of NASA Space Transportation System (STS) Payloads," all MPS payload hardware is intended and designed for repeated operations and economy (Class C), and nearly all PI's require multiple samples and multiple reflight opportunities to accomplish experimental objectives. MPS microgravity experimentation, responsive to the needs of the PI's, is accommodated through a wide variety of test capabilities:

	Typical Microgravity Duration
Drop Towers and Drop Tubes	2-4 seconds
Aircraft and Parabolic Flights	20-40 seconds
Sounding Rockets (SPAR)	4-6 minutes
Space Shuttle	
MEA	$\leq$ 7days
Spacelab Module	7-30 days
Spacelab Pallet	7-14 days
MEC	Long Duration
Space Vacuum Research Facility (SVRF)	Long Duration

Much of the MPS payload equipment can and will be employed on a number of payload carriers; for example, the single axis acoustic levitator designed for the SPAR is to be utilized on the MEA with the addition of an automatic sample changer, potentially, on the Spacelab pallet, and, ultimately, with some modification, on the MEC. Because of the interchangeability of hardware, the changing payload/investigator mission manifests, and the long term, sustaining operational nature of the MPS operational activities, UPN 6xx is intended to consolidate those activities to insure proper management control, continuity of scientific support, consistency in procedures and documentation control, and elimination of duplicative effort.

UPN 6xx, "Materials Experiment Operations," includes all of the sustaining operations such as:

- Precursory Test, Integration and Operations Support

  Ground Simulation Facilities Such as Drop Tubes and Drop Towers
  Aircraft Flights
  Sounding Rocket (SPAR) Flights (Nominally, Two Per Year)

- Orbital Reflight Integration and Operations Support for MPS Payload Carriers and Accommodation Modes

  MEA (Nominally, 2-3 Flights Per Year)
  Spacelab Module MPS Payloads (Nominally, 1-2 Flights Per Year)
  Spacelab Pallet MPS Payloads (Nominally, 2 Flights Per Year)
  MEC (Nominally, 4 Reservicing Flights Per Year)
  SVRF
  Orbiter Middeck (Nominally, 6 Flights Per Year)

- Reflight Mission Operations Support

- Payload Refurbishment, Reconfiguration, Modification, Replacement, and Reverification (Including the MPS Peculiar Payload Carriers/Spacecraft)

- PI Experiment Development for Payload Reflights

- PI Experiment Support for Payload Reflights

- GCEL Operations

- Commercial Applications (Joint Endeavor and Reimbursable Flight Opportunities) Support

The precursory test integration and operations support provide the following:

- Ground Simulation Facilities Repair, Modification, Operation and Associated Experiment Specimen Preparation

- Aircraft Payload Refurbishment, Modification, and Reverification; Payload Assembly and Integration; and Aircraft Use Charges

- Sounding Rocket (SPAR) Payload Refurbishment, Modification, Re verification; Payload Assembly and Integration; Launch Vehicle Integration; and Launch Operations

Orbital reflight integration and operations support embrace the Prelevel IV integration and the support to the Level IV-I integration that may be required for the MPS payload integrator and the PI's. Level IV-I expenses are to be budgeted by the appropriate Mission Management Office commensurate with payload mission assignments from other appropriate fund sources. Real-time reflight mission operations support, if required by either the MPS payload integrator or the PI's, would be included under UPN 6xx. Payload specialist training and mission activities are to be funded from other sources through the Mission Management Office, including those specialized activities or training required in conjunction with the PI experiment reflight work.

Payload refurbishment, reconfiguration, modification, replacement, and reverification provide the overall effort associated with the hardware, software, and documentation maintenance to accommodate the scientific and operational requirements. The reflight PI experiment activity provides analyses, ground-based research, ground-control and flight-sample preparation, real-time mission support, and post-flight analyses. Reflight PI experiment support accommodates the special analyses, testing, and hardware support unique to the PI's experiment implementation.

An essential element of spaceflight experimentation is the establishment of ground-based reference data for use in post-flight analyses. To the extent possible, the reference specimens and data must be prepared under conditions which duplicate the spaceflight conditions with the exception of the gravitational environments. The GCEL is composed of experimental equipment which is functionally identical to the flight hardware in which preflight reference specimens and data are obtained. To insure functional compatibility between GCEL and flight payload hardware, both devices must be maintained under the same configuration control system. The sustaining operation and control of the GCEL are provided under UPN 6xx.

Commercial applications entail considerable preparatory work with the private sector to find a mutually beneficial basis for cooperative- or private-funded ventures. The culmination of the preparatory work is generally realized in NASA providing integration and operations support either in a reciprocal arrangement (joint endeavor) or on a reimbursement basis. This is due to the fact that few private-sector investigators have the experience and expertise with spaceflight hardware to assume those responsibilities initially on their own. While NASA might assist in the development of commercial payload hardware, the overall thrust of the commercial application effort is to provide a self-supporting, sustaining operational basis for the exploitation of the space environment for the public benefit through the private sector; therefore, the multifaceted commercial applications are included under UPN 6xx.

In conclusion, the materials processes that can most probably be improved by operations in low gravity have been identified. They are contained solidification, including single crystal growth and polycrystalline solidification of metals and alloys; containerless solidification of crystalline and new amorphous materials; and new bioseparation techniques, among other fluid and chemical processes. Research has been initiated in each of these disciplines and some flight experiments have been defined. Table V-5 shows the evolution of the MPS program which is necessary to accomplish the essential next steps toward potential commercial applications, of which there are many.

PROGRAM EVOLUTION

Research Discipline (UPN 179)	Experimental Payloads (UPN 674)	Spaceflight Modes (UPN 6xx)	Potential Commercial Applications
Crystal Growth Processes • Diffusion Controlled Growth Phenomena • Vapor Growth Phenomena • Solution Growth Phenomena • Epitaxial Growth Phenomena • Floating Zone Growth Phenomena	Fluids Experiment Sys.(D)* Vapor Crystal Growth Sys.(D) Analytical Float Zone Sys.(B) Solidification Experiments Sys.(D) Float Zone Processing Sys.(A) Epitaxial Crystal Growth Sys.(I) High Gradient Furnace (A)	Orbiter Middeck Spacelab Module Spacelab Pallet Materials Experiment Assembly Materials Experiment Carrier (Power System - Free Flying)	Infrared Detectors Nuclear Detectors Solar Cells Doped Semiconductor Chips
Solidification Processes • Microsegregation Phenomena • Macrosegregation Phenomena • Dispersion Phenomena	Solidification Experiments Sys.(D) Fluids Experiment Sys.(D) High Gradient Furnace (A)	Orbiter Middeck Spacelab Pallet Spacelab Module Materials Experiment Assembly Materials Experiment Carrier (Power System - Free Flying)	Dispersed Composites Directionally Aligned Materials Castings Solar Cells Eutectic, Peritectic, and Multiphase Alloys Metal Foams Superconductors Miscibility Gap Alloys

*Legend: A - Under Feasibility Study
B - Under Preliminary Design
D - Under Design and Development
I - Under Industrial Consideration

TABLE V-5

Research Discipline (UPN 179)	Experimental Payloads (UPN 674)	Spaceflight Modes (UPN 6xx)	Potential Commercial Applications
Fluid and Chemical Processes • Gravity Driven Convection Phenomena • Non-g Driven Convection Phenomena • Drop Dynamics • Segregation and Flocculation Phenomena • Sterochemical Phenomena	Monodispersed Latex Reactor (D) Fluids Experiment System (D) Polymer Latex Reactor (A) Combustion Facility (A) Drop Dynamics Module (D)	Orbiter Middeck Spacelab Module Materials Experiment Carrier (Power System - Free Flying	Polymers Monodisperse Latexes
Biological Separation Processes • Electrophoresis Phenomena • Isotachophoresis Phenomena • Counter Current Phenomena • Isoelectric Focusing Phenomena • Cell Culturing Phenomena	Isoelectric Focusing System (B) Electrophoresis System (A/I) Fluids Experiment System (D) Bioprocessing System (A) Fluids Experiment System (D)	Orbiter Middeck Spacelab Module Materials Experiment Carrier (Power System - Free Flying)	Purified Hormones, Enzymes, Vaccines Purified Products of Live Cells: Blood Fraction Cell Cultures to Produce Immunologic Products

PROGRAM EVOLUTION

Research Discipline (UPN 179)	Experimental Payloads (UPN 674)	Spaceflight Modes (UPN 6xx)	Potential Commercial Applications
Vacuum Processes • Vapor Deposition Phenomena • Vapor Crystal Growth Phenomena • Outgassing and Sublimation Phenomena	Wake Shield Demonstration (A) Electromagnetic Containerless Processing System (A) Space Vacuum Research Facility (A)	Space Shuttle Materials Experiment Carrier (Power System - Free Flying) Wake Shield Free Flyer (Power System)	Purified Metals Vacuum Deposited Solar Cells
Containerless Processes • Nucleation and Solidification Phenomena • Vapor Crystal Growth Phenomena • Bubble Motion & Control Phenomena • Mixing and Shaping Phenomena • Extreme Undercooling Phenomena	Acoustic Containerless Experiments System (1-axis) (D) Drop Dynamics Module (D) Acoustic Containerless Processing System (3-axis) (B) Electromagnetic Containerless Processing System (A) Electrostatic Containerless Processing System (A)	Spacelab Pallet Spacelab Module Materials Experiment Assembly Materials Experiment Carrier (Power System - Free Flying)	High Index of Refraction Glass Fiber Optics Optical Wave Guides Laser Host Glass Microspheres, Fusion Targets Bulk Glassy Electromagnetic Materials Ultrapure Metals Variable Index of Refraction Glass Lenses Super Alloys Superconductors Property Measurements (High Temperature, Reactive Materials)