Practical Applications
of Space Systems

Supporting Paper 9

# Materials Processing in Space



A Panel Report Prepared for the

Space Applications Board

Assembly of Engineering

National Research Council

# PRACTICAL APPLICATIONS OF SPACE SYSTEMS

*Supporting Paper 9*

## MATERIALS PROCESSING IN SPACE

*The Report of the*
PANEL ON MATERIALS PROCESSING IN SPACE
*to the*
SPACE APPLICATIONS BOARD
*of the*
ASSEMBLY OF ENGINEERING
NATIONAL RESEARCH COUNCIL

*Published by*
NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D.C.
1975

# PREFACE

In November 1973, the National Aeronautics and Space Administration (NASA) asked the National Academy of Engineering* to conduct a summer study of future applications of space systems, with particular emphasis on practical approaches, taking into consideration socioeconomic benefits. NASA asked that the study also consider how these applications would influence or be influenced by the Space Shuttle System, the principal space transportation system of the 1980's. In December 1973, the Academy agreed to perform the study and assigned the task to the Space Applications Board (SAB).

In the summers of 1967 and 1968, the National Academy of Sciences had convened a group of eminent scientists and engineers to determine what research and development was necessary to permit the exploitation of useful applications of earth-oriented satellites. The SAB concluded that since the NAS study, operational weather and communications satellites and the successful first year of use of the experimental Earth Resources Technology Satellite had demonstrated conclusively a technological capability that could form a foundation for expanding the useful applications of space-derived information and services, and that it was now necessary to obtain, from a broad cross-section of potential users, new ideas and needs that might guide the development of future space systems for practical applications.

After discussions with NASA and other interested federal agencies, it was agreed that a major aim of the "summer study" should be to involve, and to attempt to understand the needs of, resource managers and other decision-makers who had as yet only considered space systems as experimental rather than as useful elements of major day-to-day operational information and service systems. Under the general direction of the SAB, then, a representative group of users and potential users conducted an intensive two-week study to define user needs that might be met by information or services derived from earth-orbiting satellites. This work was done in July 1974 at Snowmass, Colorado.

For the study, nine user-oriented panels were formed, comprised of present or potential public and private users, including businessmen, state and local government officials, resource managers, and other decision-makers. A number

---

*Effective July 1, 1974, the National Academy of Sciences and the National Academy of Engineering reorganized the National Research Council into eight assemblies and commissions. All National Academy of Engineering program units, including the SAB, became the Assembly of Engineering.

of scientists and technologists also participated, functioning essentially as expert consultants. The assignment made to the panels included reviewing progress in space applications since the NAS study of 1968* and defining user needs potentially capable of being met by space-system applications. User specialists, drawn from federal, state, and local governments and from business and industry, were impaneled in the following fields:

Panel 1: Weather and Climate
Panel 2: Uses of Communications
Panel 3: Land Use Planning
Panel 4: Agriculture, Forest, and Range
Panel 5: Inland Water Resources
Panel 6: Extractable Resources
Panel 7: Environmental Quality
Panel 8: Marine and Maritime Uses
Panel 9: Materials Processing in Space

In addition, to study the socioeconomic benefits, the influence of technology, and the interface with space transportation systems, the following panels (termed interactive panels) were convened:

Panel 10: Institutional Arrangements
Panel 11: Costs and Benefits
Panel 12: Space Transportation
Panel 13: Information Services and Information Processing
Panel 14: Technology

As a basis for their deliberations, the latter groups used needs expressed by the user panels. A substantial amount of interaction with the user panels was designed into the study plan and was found to be both desirable and necessary.

The major part of the study was accomplished by the panels. The function of the SAB was to review the work of the panels, to evaluate their findings, and to derive from their work an integrated set of major conclusions and recommendations. The Board's findings, which include certain significant recommendations from the panel reports, as well as more general ones arrived at by considering the work of the study as a whole, are contained in a report prepared by the Board.**

It should be emphasized that the study was not designed to make detailed assessments of all of the factors which should be considered in establishing priorities. In some cases, for example, options other than space systems for accomplishing the same objectives may need to be assessed; requirements for

---

*National Research Council. *Useful Applications of Earth-Oriented Satellites, Report of the Central Review Committee.* National Academy of Sciences, Washington, D.C., 1969.

**Space Applications Board, National Research Council. *Practical Applications of Space Systems.* National Academy of Sciences, Washington, D.C., 1975.

institutional or organizational support may need to be appraised; multiple uses of systems may need to be evaluated to achieve the most efficient and economic returns. In some cases, analyses of costs and benefits will be needed. In this connection, specific cost-benefit studies were not conducted as a part of the two-week study. Recommendations for certain such analyses, however, appear in the Board's report, together with recommendations designed to provide an improved basis upon which to make cost-benefit assessments.

In sum, the study was designed to provide an opportunity for knowledgeable and experienced users, expert in their fields, to express their needs for information or services which might (or might not) be met by space systems, and to relate the present and potential capabilities of space systems to their needs. The study did not attempt to examine in detail the scientific, technical, or economic bases for the needs expressed by the users.

The SAB was impressed by the quality of the panels' work and has asked that their reports be made available as supporting documents for the Board's report. While the Board is in general accord with the panel reports, it does not necessarily endorse them in every detail.

The conclusions and recommendations of this panel report should be considered within the context of the report prepared by the Space Applications Board. The views presented in the panel report represent the general consensus of the panel. Some individual members of the panel may not agree with every conclusion or recommendation contained in the report.

# PANEL ON MATERIALS PROCESSING IN SPACE

Winfield W. Tyler (Chairman)*
Xerox Corporation
Rochester, New York

Robert E. Hughes (Co-Chairman)
Cornell University
Ithaca, New York

Manuel Aven
General Electric Company
Schenectady, New York

Harry C. Gatos
Massachusetts Institute of Technology
Cambridge, Massachusetts

John P. Howe
General Atomic Company
San Diego, California

Kenneth A. Jackson
Bell Telephone Laboratories
Murray Hill, New Jersey

Louis R. McCreight
General Electric Company
Philadelphia, Pennsylvania

Albert L. Rubin
Rogosin Laboratories
Cornell University Medical College
New York, New York

David A. Stevenson
Stanford University
Stanford, California

*Dr. Tyler served as chairman of the Panel during the organization of the study and the deliberations at Snowmass; Dr. Hughes served as chairman during the subsequent drafting and editing of this report.

## ACKNOWLEDGEMENT

The Panel wishes to express its sincere appreciation to the following persons who made themselves available for consultation and who contributed significantly to the work of the Panel by providing background information and briefings as needed:

Tommy C. Bannister
NASA Marshall Space Flight Center
Huntsville, Alabama

William T. Carey
NASA Marshall Space Flight Center
Huntsville, Alabama

Howard W. Etzel
National Science Foundation
Washington, D.C.

Lawrence C. Kravitz
Air Force Office of Scientific Research
Arlington, Virginia

G. V. F. Seaman
University of Oregon Medical School
Portland, Oregon

Gunther Seibert
European Space Research Organization
Neuilly-sur-Seine, France

In addition, the staff of the Space Applications Board wishes to express its appreciation to the following persons who -- while they bear no responsibility for the material herein -- provided expert advice in connection with the final editing of that section of the report of the Space Applications Board which deals with electrophoresis and with the processing of biological materials:

John Adamson
The University of Washington
Seattle, Washington

Milan Bier
Veterans Administration Hospital
Tucson, Arizona

Harold Burlington
Brookhaven Laboratories
Stony Brook, New York

King Engle
National Institutes of Health
Washington, D.C.

Allen Kaplan
National Institutes of Health
Washington, D.C.

Alan Rosenthal
National Institutes of Health
Washington, D.C.

CONTENTS

CONTENTS (continued)

# INTRODUCTION

The 1974 Summer Study on Practical Applications of Space Systems included a Panel on Materials Processing in Space to assess the feasibility and possible advantages of processing materials in a nongravitational field. No similar panel was included in the NAS 1967-68 study on useful applications of earth-oriented satellites, which served as a point of departure for the 1974 study. Therefore, this introduction includes a brief history and review of progress to date in this field.

Processing of materials in space is in an embryonic stage. Potential availability of sufficiently large spacecraft for both launching and recovery of useful payloads offers a new dimension for applied research and processing of materials. This availability of prolonged near-zero gravity encourages one to identify materials processes which are adversely affected by gravity. Other aspects of the space environment (for example, vacuum pumping capacity, space radiation fields) may also be useful adjuncts to the low gravity available in space.

A few examples of innovative ideas and practices are available to illustrate early applications of processing at zero gravity. The ideas evolved in the mid-1960's, primarily from some personnel at the NASA Marshall Space Flight Center and NASA Headquarters. A few indications of how bubbles and droplets behave in near-zero gravity were observed and recorded during some Apollo flights (References 1 and 2). These early ideas effectively stimulated discussions which produced new ideas, which when analyzed became, in some cases, the base for flight demonstrations.

During these early and formative years of the program, there were many contacts with potential industrial users. Perhaps prematurely, these contacts were aimed at involving industrial users in a very direct, supportive manner. It is the results of Apollo and Skylab flight experiments, as well as future flight results, which will largely determine user response to the future benefits of materials processing in space. Early demonstrations and flight experiments were usually conducted on simple materials used as models and using simple versions of the processes of interest. The objective of this Panel study is to encourage future experiments that will be both more definitive and more focused toward the most viable areas for obtaining practical benefits from space processing. The interest of potential users is expected to increase when the results of these future studies and experimentation from the early years of the Spacelab and Space Shuttle become available.

Since the inception of the NASA Space Processing Applications Program (previously known also under such other titles as Materials Science/Manufacturing in

Space, for example), small contractual research and technology programs have grown in number from about 5 to about 70 contracts per year. More than 20 demonstrations and experiments were initiated and carried out on Apollo flights 14, 16, and 17 (References 3 to 7) and on the Skylab flights (References 8 to 10) to demonstrate or test space processing ideas and principles. The experiments were often planned, scheduled, designed, and constructed on very short schedules. As might be expected, some experiments gave interesting and unexpected results and others gave indeterminate results. Many of the analyses and studies of samples returned from Skylab early in 1974 had not yet been completed and reported at the time of the 1974 Summer Study. Thus, the deliberations of the Panel were based primarily on published preliminary Skylab results (Reference 11) and on briefings, primarily by NASA personnel and in a few cases by the principal investigators of these flight experiments. Also included was an excellent review by the European Space Research Organization (ESRO)* of European work in this field (Reference 12).

The following observations and results from flight demonstrations accomplished to date were deemed significant in considering the need for further research and development:

Diffusion controlled solidification of crystals was obtained;

Containerless crystal growth with high surface perfection and low dislocation density was demonstrated;

Results from experiments on immiscible metals were judged of sufficient interest to pursue further;

Heat flow and convection can be reduced and controlled under low gravity but convection is not necessarily eliminated; and

Preliminary demonstrations of electrophoresis on two Apollo and one Skylab mission indicated promising possibilities for purifying and separating biological materials.

These preliminary results and others helped to provide input to and serve as the foundation for the recommendations of the Panel for further research and development, as well as for flight experiments in the field of materials processing in space, which are discussed in this report.

It should be noted that NASA has established significant interactions with the biological community in the past years (Reference 13).

Finally, the Panel acknowledges and appreciates the substantial contribution and recommendations by the Universities Space Research Association (Reference 14).

*Since the study, ESRO has become the European Space Agency (ESA).

# CURRENT USER NEEDS

Because materials processing in space is in the research and development stage, the user at this time is the research segment of the materials application community. The eventual users will be the industrial and commercial organizations who can best utilize the research results in the products which they offer to consumers. However, processing of materials in space is likely to be applicable to only one step (or at most a few steps) of the many necessary to the production of, for example, a biological or an electronic device. Space processing should therefore be viewed as only one of many steps in an overall manufacturing sequence.

The Panel believes the potential benefits of materials processing in space can best be achieved if NASA continues its program of initial research and development and launch services, but with a gradual transition to direct relationships between NASA and the industrial organizations in the private sector who would determine their needs, compare benefits with costs, and arrange for processing of their materials in space when they consider it cost-effective.

Biological products such as vaccines, serums and hormones are high-value, low-volume products, and the potential benefits from space processing could be large if certain of these products could be prepared in purer form, or with greater specificity, in space than on earth. It is not unreasonable to expect that new products, currently impossible to manufacture at the surface of the earth, might be developed.

One can estimate the potential value of new or improved biological products by two complementary approaches. First, if improved serum for use in the transplantation of kidneys (as well as of other organs) could be provided, and if suitable hormones (such as erythropoietin) or other biological products could be manufactured, improved health could be brought to the some 15,000 persons in the United States who suffer from renal failure. While other examples could be presented, the cited case has an extra aspect of importance by virtue of the fact that these kidney treatments and transplants are federally supported. There can, therefore, be a fairly direct measure of the costs and perhaps a more exact measure of the benefits of rehabilitation of persons as well as a more clear-cut rationale for government research and development to reduce these expenditures.

Alternatively, the estimation of cost benefits could be based on the effects on the pharmaceutical industry of successfully developing processes for making products of higher purity. This industry has annual sales of about $8 billion in the United States, of which about 5 percent is in biologicals. A significant fraction of these biological products might benefit from space research on purification.

In the case of the inorganic materials, also recommended by the Panel for attention in the materials research and processing in space program, applications are much more diverse in terms of both the number of industrial organizations that might utilize the results or products and the variety of uses. This makes it more difficult to estimate the economic impact. Nevertheless, some estimates, which the Panel believes are conservative (detailed in subsequent parts of this report), indicate a possible direct value of $8 million to $40 million per year in domestic sales with considerable leverage on costs of related products. The dollar value of products sold abroad is likely to be several times this amount. Thus, substantial benefits may be transferred to other countries at the same time that the U.S. balance of payments is favorably affected.

In addition, there may be expected numerous other, less visible, socioeconomic benefits both in the health-care field and throughout industries that use inorganic materials, discussed later in this report.

The initial and continuing cost of the space program is paid for ultimately through tax revenue, much of which is collected by U.S. commerce and industry in connection with their role of providing goods and services to the consumers. The basic interest of both the public and private sector organizations involved in space processing should therefore be the same, namely, to provide the best goods and services possible for the least cost.

It is therefore suggested that, because the nature of current activities is in the research and development stage, NASA should maintain its current role directed toward the pursuit of those development opportunities, as far as possible, which are conducive to attracting private enterprise. This effort is believed to require considerably more demonstration of the technical feasibility for exploring the benefits of low gravity processing. The successful development and demonstration of the Space Shuttle, the achievement of the expected operating costs, and suitable arrangements for allocating costs, benefits and rights will benefit the consumer through improved products, industry through technological improvements, and government through continued increased income from a broadened economic base.

# BIOMEDICAL APPLICATIONS

## BACKGROUND

In this section, the Panel will recommend vigorous and systematic development of processes for separating, characterizing, and analyzing biological materials in the absence of gravitational forces. Our recommendations are based on the following considerations:

Benefits: Potentially, several thousand human lives may benefit from the improved isolation and production of any one of several known enzymes, hormones, immunological factors and cells. Knowledge at hand from biology and medicine provides confidence that beneficial applications of these entities exist. The breadth and the vigor of the biomedical field of research led the Panel to believe that in the course of the 15-to-20 year lead time expected for development and evaluation of complete processes for producing materials in space, additional highly valuable biomedical materials and functions will be discovered in the course of research in laboratories on the ground.

There are several processes for the preparation of biologicals which might benefit from one or more aspects of the space environment. Of these, perhaps the most widely used analytical procedure, electrophoresis, is also the one that could possibly be most beneficially exploited to provide useful quantities of higher purity biologicals if it could be scaled up to meet both quality and quantity requirements.

The Usefulness of Electrophoresis: The electrophoretic motion of biological molecules, complexes, and cells through an appropriate aqueous solution in an electric field (and other potential gradients) is used extensively for analyzing, characterizing, and separating these biological entities. It is estimated that as many as 20,000 to 30,000 technicians and researchers are using this technique for diagnosis and research. Over 300 research papers per year are published in this general field. Thus, the technique has both a proven basis and an extensive future potential.

Improving Electrophoretic Processes: In laboratories on the earth's surface, gravitational forces induce an unwanted mixing which reduces or may even prevent the separation of biological and other fluid components by the very weak forces involved in the electrophoretic process. Improvements in resolution and specificity of the process have been predicted analytically and to some extent confirmed in experiments in space. The Panel considers that the possibility exists of realizing important benefits from electrophoretic processing of biological materials in space.

## GENERAL NATURE OF PROGRAM

The systematic development of processes will require a systems approach including carefully designed scientific and engineering experiments conducted on the ground, in simulated flight, and in orbiting vehicles. A major objective of the design of experiments should be to determine and relate the significant variables (some of which will be outlined subsequently) necessary for the evaluation, engineering, operation, and control of cost-beneficial processes and medical applications. To complement the experiments, there needs to be a program of theoretical analysis designed specifically to complete the application of fluid-electrothermodynamical theory to the several useful processing systems. Finally, there need to be developed the process steps, procedures, and quality assurance that must precede and follow processing in space in order to obtain, preserve, and deliver the medical materials. This systems concept requires both interdisciplinary and multi-institutional efforts and perhaps new inter-institutional arrangements.

## STAFFING THE EFFORT

The systems approach to the problem will require collaboration and integrated efforts among physical-biochemical, medical, and fluid dynamical researchers, along with analytical, design, planning, and quality-assurance engineers, and medical specialists and practitioners. Since the development and evaluation of these processes will extend beyond 15 years, the program must attract and motivate young talent. Through competitive collaboration and exchange between ground- and space-oriented teams, both objectivity and success may be fostered.

## BASIS FOR RECOMMENDATIONS

An outline of known recent progress in the evaluation of processing of biomedical materials in the absence of gravitational forces as well as of a few trends in medical research will reveal the reasons for the Panel's general recommendations and provide a basis for what the Panel is able to project in the way of future programs.

The primary sources of information on the processing of biomedical materials are the Universities Space Research Association (Reference 13), the European Space Research Organization (Reference 12), Panel members A.L. Rubin and L. R. McCreight

(Reference 15), and advisors and consultants G. V. F. Seaman, G. Seibert, T.C. Bannister and W. T. Carey.

There is partial confirmation that increased resolution can be achieved by using electrophoretic separation in the presence of low gravitational forces. In an electrophoresis demonstration using dye molecules, sharper boundaries were observed on Apollo 14 than had been observed on earth (Reference 3). Improved separation of polystyrene particles, compared with control experiments in an earth laboratory, was observed in an Apollo 16 demonstration.

At the present time, biological separations of particular interest include the following cases demonstrating or illustrating opportunity:

> Isolation of those kidney cells that produce the hormone erythropoietin that in turn stimulates the production of red blood cells in bone marrow. Thousands of patients with kidney disease are severely anemic for lack of the hormone.
>
> Isolation of those kidney cells that produce the enzyme urokinase, now in large demand to eliminate emboli from the circulatory systems of patients.
>
> Isolation of subpopulations of white blood cells (lymphocytes) and production of antibodies and other products (from lymphocytes) that characterize and may modify the immunoresponses of patients to transplants, nucleation and growth of tumors, and other therapies or pathologies.
>
> Identification and isolation of blood proteins that are associated with clotting and other behavioral features of blood, with anticarcinogenicity, and with other functions such as the metabolism of neurochemicals.
>
> Identification and isolation of fractions of red blood cells (erythrocytes) having different electric charge, dipole layer (zeta potential) density, and other characteristics, particularly as model substances.
>
> Identification and separation of nerve cells having different electrolytic, internal electric, neurochemical and neurological behavior and functions.

## PROGRESS IN DESIGN OF ELECTROPHORETIC PROCESSES

Principles of the apparently useful techniques in electrophoretic processes may be outlined in the following elementary fashion that may suffice to rationalize the future program taken up in a subsequent section.

> Macroscopically, biological particles (molecules, complexes, cells, etc.) are differentiated and separated through their

trajectory or position under rather complex forces in an aqueous electrolyte.

Microscopically, a particle is characterized by its charge, volume, shape, density, and degree of binding to molecules and ions in each particular solution.

The charge on a particle is determined by its surface functional groups, carboxyl, amino, other proton donor and acceptor groups, or acid-base groups, other ion acceptor and donor groups and, in some cases, electron acceptors and donors. Cells within a given type apparently may vary in these respects within limits. Thus, the donors and acceptors in the aqueous electrolyte in turn determine the charge, oxidation state, surrounding charge distribution or ionic atmosphere and, often, size and shape of the particle.

The motion of a particle is diffusional, or Brownian, biased by a local force field made up of externally applied fields (electrical, gravitational, and fluid flow), modified by usually small, induced ionic and molecular redistribution. If the local field is simply related to the applied field, the response of the particle is described by a mobility that lumps the characteristics of the particle with those of the solution. For the latter, viscosity, density, and ionic strength often suffice. All of these response coefficients depend on temperature.

Local forces that are difficult to quantify and flows that may seriously perturb response to the known or fixed external fields are convection due to gravity acting on density gradients or differences which in turn depend on temperature and composition gradients; interfacial energy gradients which may include temperature and composition; and electrical potential gradients and fluid velocity gradients near walls or other interfaces.

Thus, while gravitational forces can be used to advantage in some processes (for example, in sedimentation), in the electrophoretic process their absence allows definitely better control of the motion of large particles, both relative to the electrolyte and relative to the external frame of reference, namely, the regions of introduction or removal from the solution.

Similarly, but only within trade-off limits, increasing distances between particles and walls or other high energy interfaces assist in controlling or knowing particle motion.

By eliminating or reducing gravity-, density-, and thermal-gradient effects and serious interfacial effects, advantage can be taken of utilizing pH, ionic strength and viscosity levels, and gradients over a significantly wider range further to characterize and separate particles (Reference 4). Obviously, biological considerations place limits on the temperature in any volume element of the solution.

Techniques of several kinds are permitted by the principles just discussed and are used for the analysis of biological particles. In turn, some of the techniques may be considered for separation of relatively large quantities of biological substances. References 12 and 13 contain descriptions of the principal methods. A brief description of the techniques follows.

Crossed or orthogonal electric and laminar flow fields provide an effective analytical and separation procedure for many kinds of particles as discussed in References 12 and 13, and particularly by K. Hannig (Reference 12) who makes clear the modifications in design and performance afforded by reduction of gravitational forces. In this apparatus, laminar fluid flow is confined between two rather closely spaced flat plates. Electrodes at either side produce a homogeneous electric field in the electrolyte, which flows normal to the field. Particles to be separated are introduced at the upstream end and removed at selected ports along the edge at the downstream end, which is a distinct advantage for preparative purposes. This technique separates particles on the basis of their charge and mobility. While in principle pH and ionic strength could be adjusted to vary normal to the flow of the electrolyte, it is more difficult to simultaneously vary the viscosity in a controlled manner. Thus, some of the more subtle differentiations of biological particles will most likely not be done by this method.

Given adequate differentiation of particles for selected constant electrolyte properties, the main factors that decrease resolution are associated directly or indirectly with the walls. As mentioned before, gravitational forces influence apparatus size. Viscous drag, electrokinetic effects due to charge distributions near the wall (that differ from those in the bulk solution), and temperature gradients affect particle velocities in the laboratory frame of reference rather significantly. For a given electrolyte, wall materials and treatments may be chosen to minimize electrokinetic effects. On the other hand, joule heating of the electrolyte causes a temperature differential between the center and the wall and results in convection, if gravity and density changes exceed certain values. In the absence of gravitational forces, a temperature rise affects viscosity and mobility, which may not be serious, and biological and biochemical behavior, which may be very serious. Experience in developing the M-570 Skylab experiment (Reference 11), later verified by K. Hannig (Reference 12), has established that in the absence of gravitational forces, practicable wall spacings may be increased from 1 or 2 mm to between 5 and 10 mm. Thus, resolving power and throughput may be increased significantly. To the Panel, this design improvement seems significant, at least for particles that are well characterized as to mobility and charge.

Another technique uses columns having a stationary electrolyte in a longitudinal potential gradient that separates particles into groups moving at equal speeds (isotachophoresis). In this case, with gravity present, sedimentation interferes. Further differentiation of particles having the same charge-mobility product may be needed. In such a column, gradients of viscosity, pH, and ionic strength may be introduced to provide additional differentiation. Simple demonstrations of electrophoretic motion and separation using the moving boundary method were done on Apollo flights 14 and 16 as forerunners of future experiments. The results were not decisive but they appear to be favorably indicative.

A third technique introduces regions of controlled pH which, for given ionic strength, trap particles having acid-base properties such that they are not charged at the given pH. Acid-base equilibria rather than charge and mobility provide differentiation in this method. Again, sedimentation resulting from gravitational forces interferes.

Clearly, variations on these techniques, together with many other possibilities (depending on the physical-biochemistry of the particles and on the degrees of freedom added by the absence of gravitational forces) are possible. Worth exploring are the possible advantages of avoiding solid walls altogether, except in electrode regions. Liquid-gas and liquid-liquid interfaces widen the possibilities for modifying interfacial charge distributions (zeta potential) and thus, flow near interfaces. While these numerous effects and variables offer a rich field of research and the possibility of many refinements in preparative techniques, the task of selecting optimum conditions for space processing is formidable. Of course, workers in the field are familiar with these and many other considerations. A major point of this discussion is that the many potentially useful phenomena and relationships must be translated into engineering.

## COMMENTS ON FUTURE PROGRAMS

### Philosophy of Approach

It appears to the Panel that at the present time one has the difficult and largely subjective task of trading off between rather different kinds of approaches, the extremes of which may be indicated as follows: (1) select one or two processes for about as many products and systematically determine relationships among basic process variables and parameters of the type previously outlined as required for successive scale-up of production rates; (2) make preliminary trials of fairly large numbers of techniques and materials with the hope of both finding reasonable process conditions and producing at least one important biomedical material or effect in at least one experiment.

The total possible number of process variables is very large and the number of biochemical-electrolyte variables associated with living cells can be enormous. Before processing experiments can be carried out in space, the number and range of the variables must be minimized around an expected optimum. Thus, the Panel leans toward the first approach sketched in the preceding paragraph.

However, room for intuitive exploration and serendipity must be provided because not all of the important possibilities can be included in any single approach. As a proposal for discussion, the Panel suggests that enough effort, including optimal experimental design, be put on separating reasonably well-characterized cells to settle crucial questions about techniques and conditions for processing cells in the space environment. Selection might be made by a task force of knowledgeable and inventive biochemical and medical researchers. In addition, about one-half as much support might be placed on wider exploration of techniques, phenomena, and materials. Use of gravitational forces, as well as quantitative prediction of the results of reducing them in separation processes, should be exhaustively treated.

The Panel notes a moral question connected with a narrow choice of biomedical products. This choice affects the lives of a particular set of patients and medical practices, perhaps to the neglect of other sets. Thus, the choice is an important one.

Selection of Electrophoretic Processes

The Panel has learned from the literature and discussion that the technique using orthogonal, electrical, and laminar flow fields, called continuous flow electrophoresis, is preferred on the basis that continuous operation favors throughput and that wide spacing of the walls to between 5 and 10 mm will reduce wall effects sufficiently to provide adequate resolving power. This issue of trading off increases of temperature in the solution (due to distance for heat flow and no convective transport) against reduced wall effects will no doubt be settled in ground-based laboratories and an optimized spacing used in orbiting vehicles.

Insofar as analysis and characterization are concerned, the Panel's preliminary opinion is that the unique physical-biochemical conditions afforded by reasonably independent adjustment of viscosity, pH, and molecular and ionic composition (including their variation with position in the cell) will be taken advantage of to resolve particular biological questions. Hopefully, complementary earth-based studies will maximize the number and importance of results from analogous experiments in orbit. Quite likely, some of these analytical techniques will lead to production methods -- particularly for the specific biomedical substances that respond to the features of the analysis.

Dr. A. L. Rubin made it clear in Panel discussions that the success both of the research and development leading to production of biomedical materials in space and of the health service made possible by this research depends entirely on having the techniques, procedures and skills for preparing, preserving, and delivering the required substances. The Panel is aware that the pharmaceutical and medical product industries, hospitals, and the medical profession are versed in these matters. However, an advance such as separating, culturing, and exploiting special cells to produce an important therapeutic service will probably be greatly facilitated by increased interdisciplinary and inter-institutional collaboration, perhaps to the extent that new disciplines and institutions will appear.

Several biological experiments are planned for the Apollo Soyuz Test Program (ASTP). These varied and preliminary experiments may be expected to provide valuable guidance to future studies.

## ELECTROPHORESIS IN NONBIOMEDICAL SYSTEMS

Several nonbiomedical systems may benefit from electrophoretic experiments in zero-gravity environment. These systems include suspensions of wood pulp fibers used in manufacture of paper products; suspensions of clays, of importance to soil sciences, soil engineering, and water softening; and complex suspensions of oil, sand, and water encountered in oil shale exploration. None of these systems appears to warrant high priority compared to biomedical systems.

# PROCESSING OF INORGANIC MATERIALS

Although materials processing in space has been the charter of a separate panel in the 1974 summer study, the various devices used in carrying out the mission of several of the other panels, such as Uses of Communications, Weather and Climate, and Land Use Planning,* are ultimately based on advanced electronic, optical, and structural materials. Research and development on materials processing in space is characterized by an interplay between striving toward new or improved materials and the physicochemical phenomena involved in their synthesis (just as it is on earth, the principal difference being the magnitude of the gravitational force). The very process of synthesizing a new material often leads to recognition of a new phenomenon and, conversely, the application of a newly recognized phenomenon in preparing a material may lead to a substance with new and sometimes unexpected characteristics.

The absence of gravitational pull may be expected to allow us to improve those characteristics of materials that are adversely affected by gravity when processed on earth, for example, crystalline perfection, homogeneity of precipitation in multiphase systems, and purity. But, just as important, the absence of gravity in space may reveal phenomena based on forces (such as, for example, surface tension) that are overshadowed by gravitational effects in earth-based processes.

Many phenomena and the preparation of many materials are thus expected to be influenced by the absence of gravity. However, in its selection of model systems and model phenomena for experimentation, the Panel has restricted itself to only about half a dozen high-priority items. This rationale is based on the opinion that results from the few high-priority experiments suggested will invariably lead to more experiments and more ideas for follow-up, as is characteristic of divergent exploratory research.

At the same time, several of the experiments chosen involve materials of significant commercial potential, so that even preliminary results of basic scientific nature may yield significant guidance for how to better utilize and

---

*Panel on Uses of Communications, Panel on Weather and Climate, Panel on Land Use Planning. *Practical Applications of Space Systems, Supporting Paper 2: Report of the Panel on Communications; Supporting Paper 1: Report of the Panel on Weather and Climate;* and *Supporting Paper 3: Report of the Panel on Land Use Planning.* Reports to the Space Applications Board of the National Research Council. National Academy of Sciences, Washington, D.C., 1975.

process these materials on earth. The Panel has also attempted, in its selection of high-priority experiments, to include materials of several classes: elemental and compound semiconductors having narrow energy bandgaps, compound semiconductors having wide bandgaps, single and multiphase systems, and metals of high and low melting point. The selection was made on the basis of experiments already performed on Skylab, those proposed for the ASTP flight, and ideas generated during the Panel sessions.

Another factor that must be considered in the selection, execution, and utilization of materials synthesis, on earth as well as in space, is that one small improvement and/or observation leads to another, often in a "random walk" pattern. The Panel, therefore, believes that greater benefit would come from a large number of small and medium size experiments than from a few large or elaborate ones. The Panel also believes that for each proposed experiment to be carried out in space, there should be a concerted effort to try to achieve the same or better result on earth. In fact, the opportunity to compare results obtained in space and on earth initially may be the most important benefit from the space experiments.

## VAPOR TRANSPORT GROWTH OF SINGLE CRYSTALS

There is significant interest in vapor transport processes for the growth of single crystals; for example, this technique is important in the preparation of semiconducting and insulating crystals and thus is of substantial commercial interest. One parameter of importance is the effect of convection in the growth region caused by density and temperature gradients. Consequently, there is a reasonable probability of significant differences in the growth process in the earth and the space environment. This phenomenon was investigated in Skylab processing experiment M-556 studying vapor growth of germanium selenide and germanium telluride in closed ampules using a halogen transfer agent. The results indicated some measurable differences in the mass transfer rates and crystal quality. The opinion of the Panel is that this general area of research should be explored further; however, it is deemed prudent to study a system for which there is better knowledge of growth parameters and crystal gradients in ground-based experiments (and one which is also of greater practical interest).

It was recommended that gallium arsenide be grown by vapor transport in a closed ampule with a halogen transfer agent. Two classes of experiments -- self-nucleated crystal growth and seed-nucleated crystal growth -- are suggested.

## IMMISCIBLE METAL ALLOYS

There are many metal alloys which exhibit immiscibility in the liquid phase. It should be possible to obtain these liquids as two-phase suspensions on a fine scale in space. It is expected that in zero gravity, the size of the suspended phases will be limited by Ostwald ripening rather than by gravity-assisted agglomeration as in ground-based experiments. Preliminary experiments on Skylab (e.g., M-557) have indicated that solidification of such a fine two-phase suspension can result in phases which are not observed in ground-based experiments. If this result is substantiated, it opens up the possibility of obtaining a variety of new phases, dispersed on a fine scale. It is impossible to predict at present which of these new alloys will be important or, indeed, which of their properties will prove to be unique. However, the Panel believes that this method of preparation should be pursued with a view to obtaining alloys with unique properties.

## MECHANISMS OF GROWTH FOR SEMICONDUCTOR CRYSTALS

The growth rate and interface shape of a semiconductor crystal can be measured and delineated by using a timed sequence of short-duration current pulses through the growing crystal. These pulses produce a brief increment of increased or decreased growth rate due to Peltier heating or cooling. These effects can subsequently be revealed on sections of the crystal by etching or other methods. In extensive ground-based experiments, these methods have given increased understanding of facet formation during crystal growth and of the inter-relationship between convection, growth rate fluctuations, and the distribution of impurities and dopants in the crystals. These experiments should be conducted in a zero-gravity environment to examine faceting effects and the distribution of impurities in the absence of convective effects. Indium antimonide and germanium are suggested as the most suitable model systems.

## SOLIDIFICATION IN SPACE ENVIRONMENTS AND PREPARATION OF DISLOCATION-FREE METALS

The space environment has three unique features which relate to solidification: the absence of gravitational forces on the solid phase; the ease of levitation and consequent solidification of a liquid without a supporting mold; and the absence of convection in the liquid due to density and temperature gradients.

In the case of metals, which are extremely weak at their melting points, gravitational fields and metal-mold forces due to the disparity in thermal expansion coefficients may cause plastic deformation during solidification with the introduction of dislocations. There is presently interest in the production of dislocation-free metals for basic metals physics studies. One approach on earth is the use of well-controlled solidification conditions with very soft molds so that the mold deforms in preference to the metal. The Panel suggests that a measurable improvement in dislocation densities may be attained be levitation melting in space environments, followed by seeding and heat-sink processes. Preliminary results, indicating some promise, were obtained on Skylab.

It is proposed that experiments in controlled solidification processes be made on several metals such as tin, silver, tungsten and beryllium. The former two are chosen as model systems, whereas the latter are chosen for the interest in the preparation of high quality tungsten as targets in X-ray tubes and the possible applications of high quality beryllium for neutron spectrometers.

## OTHER EXPERIMENTS

In addition to the experiments already discussed, there are severa reas where there exist possibilities for significant experimentation. We have not been able to identify particular experiments in these areas, but would not like to preclude the possibility that those can be devised. One is in the area of certain special purpose glasses or ceramics, where containerless processing may have some advantages such as reducing impurities and reducing heterogeneous nucleation. It is noted that convection is normally not a problem in glass preparation because of the high viscosity of the melt. It is also noted that in conventional processing of glasses, gravity serves to eliminate bubbles. If processing of glasses or ceramics in space appears to have advantages, this and possible other problems arising from the absence of gravity will have to be addressed.

Another area is purification where containerless processing may provide a viable alternative to crucible methods, and where earth-bound levitation methods cannot be applied.

Convection is know to play an important role in the structure of castings. Convective effects can often be controlled adequately on earth, but there is a possibility that careful experimentation in zero-gravity will lead to new insights into casting processes.

Other phenomena, especially those relating to fluid mechanical effects, are worthy of exploration in zero-gravity. These include the effects which are masked or diminished on earth by gravity-driven convection, such as the Marangoni effect.

The synthesis and handling of ultra-small particles is currently of interest to the materials community, and zero-gravity appears to provide unusual possibilities; however, no systems and experiments are identified at present.

No advantages could be identified for attempting to synthesize membranes in space for biological applications. Polymer processing, which is by and large a bulk processing industry, is unlikely to find any advantage in space processing.

Directionally solidified eutectics show promise for use in high-temperature turbine blades. It is not clear at present how space processing would significantly affect this technology.

Composite materials for structural applications made by incorporating fibers into a matrix usually have a sufficiently large volume traction of the fibers that sedimentation is not a problem. Similarly, fine particle dispersions for strengthening do not present serious sedimentation problems.

It is considered at present that silicon technology is well advanced and it is unlikely that processing at zero-gravity could have a significant impact on this technology. In addition, the electronics industry uses primarily thin film and epitaxial methods for semiconductor processing. Space processing is unlikely to have a significant impact on these technologies. Power circuits could conceivably benefit from increases in the size and perfection of silicon single crystals. At present, silicon crystals of 15 cm in diameter have been grown on earth. Until such crystals have been used in practical devices, the Panel does not recommend trying to grow even larger crystals in space.

It seems reasonable to expect that continuing studies and searching for new opportunities will be emphasized in ground-based research by NASA, industry, and university groups during the coming year.

## DISCUSSION

The experiments which have been outlined were selected because they would provide general information about phenomena and processes in space in addition to the intrinsic merit. In instances in which they lead to interesting results, these experiments should be pursued in a manner to maximize their impact on our ability to manipulate and control material properties.

The Panel cannot, at the present time, identify with assurance any specific space processes which it would expect to lead to well-defined cost savings as compared with processing on earth. The rate at which such processing will progress can be predicted within certain limits. For example, the Spacelab experiments will not begin until 1980; presumably, some time will elapse then before a particular process is identified and demonstrated as feasible and advantageous for space manufacturing. In the high technology industries, there is usually a period of 10 years between this point and when the item is in manufacture. For space processing, this period could well be longer because of the intermittent nature of the opportunities for research and development activities in space flight. Thus, in the opinion of the Panel, it is likely to be well into the 1990's before profitable manufacturing in space is even a possibility. This time lag clearly affects the potential return on investment for research in this area and indicates as well that space processing will have to be competitive with the ground-based manufacturing technology which will exist twenty years from now.

Although reasonably accurate cost and benefit analyses can be performed for contemporary space missions and acceptable approximations are possible for the emerging areas, materials processing as a future activity in space suffers from the lack of an adequate data base on which to formulate a credible cost and benefit analysis.

Specifically, the semiconductor, opto-electronic, and other specialty materials industries are growing and changing so rapidly that the validity of estimates based on what we know in 1974 would be highly suspect during the research missions of the 1980's and might be totally misleading for the processing missions of the 1990's. Yet the most interesting developments in space processing of inorganic materials are in these special materials.

Perhaps two examples, the transistor and the laser, will best illustrate the character of the specialty materials industries. Forecasts of the dollar volume of transistor-based commerce in the 1970's, made in the late 1940's when monies were being alloted for research on development of the transistor, were grossly underestimated. In the case of the laser, estimates made as recently as ten years ago are not valid today.

Materials of interest to the specialty materials industries include:

> Certain compounds of elements such as germanium, silicon, gallium, and arsenic, which are used in microwave devices, semiconductor lasers, infrared detectors, light-emitting diodes, cold emission cathodes, solar cells, thin film optical circuits, bulk and semiconductor devices and radiation detectors.

Certain specialty metals and alloys, including tungsten used in X-ray tube targets, beryllium used in neutron spectrometry, and super-alloys for a variety of uses demanding good characteristics at high temperatures and great mechanical strength.

Certain materials used for superconducting elements, such as alloys of niobium and tin.

The total commerce based on just the listed semiconductor, opto-electronic, and noncommodity solid-state materials can be roughly estimated to be between 1 and 5 percent of the nonservice part of the gross national product today and is known to be growing faster than the nonservice part of the GNP. Taking $1000 billion as the rough figure for the GNP today, if 40 percent of it ($400 billion) constitutes the nonservice component, the Panel believes that commerce using the above materials in one way or another today represents about $4 billion.

Assuming that space processing will affect 1 percent of the applications of solid-state materials -- an assumption the Panel believes is conservative -- there is a leverage of between $40 million and $200 million of products. Assuming further that in the affected applications, space processing will produce a 20 percent improvement in cost (better yield, better quality, higher power, etc.), the Panel estimates a potential yearly incremental benefit of between $8 million and $40 million, or a cumulative $48 million and $240 million for six years. The six-year cost of the space processing flight program discussed subsequently in "Shuttle and Spacelab Flight Program Costs," including both inorganic and biomedical materials, is estimated at $120 million (excluding flight costs). If approximately one-half of that $120 million is allocated to biomedical experiments, this leaves roughly $60 million as the cost for inorganic materials. If the Panel is correct, that its estimates have been conservative, and noting that it has not taken into account the growth of the industry and any fallout benefits, the Panel believes that the cost-benefit ratio for space processing of inorganic materials can be expected to be quite favorable.

# FLIGHT PROGRAMS AND FUNDING

## SOUNDING ROCKET PROGRAM

A brief review of the planned NASA program for materials processing using sounding rockets was conducted by the Panel. Sounding rockets appear to have significant value to provide needed flight opportunities for the time-interval between 1975 and 1980, that is, between the Apollo Soyuz Test Program and the first Space Shuttle mission. The Panel selected as most likely prospects for the sounding rocket program experiments in electrophoresis, immiscible alloys, solidification, and levitation. Results from these experiments will serve to complement ground-based research in progress during this time-interval and will provide excellent background information for the planning of more advanced and sophisticated experiments to be done in Shuttle missions in the early 1980's.

## UTILIZATION OF SHUTTLE AND SPACELAB

In order to carry out the envisioned research and development activities on materials processing in the Shuttle/Spacelab era (1980 and on), three types of flight opportunities are required, as described below.

### Spacelab Missions

The equivalent of two dedicated Spacelab missions per year should be made available to accommodate materials processing payloads located in the habitable portion of Spacelab and on the pallets. The experimental equipment, which it is expected would closely resemble that of a ground-based laboratory, would fully capitalize on the presence of an experimenter who would control experimental conditions, and change them as required, observe the experiments in progress, and occasionally consult with principal investigators located on the ground. It is postulated that the optimum flight frequency from a user viewpoint would be about four to eight flights per year, each of which would require about one-fourth to one-half of Spacelab mission resources (weight, volume, crew time, power, etc.). The mission could thus be shared with another discipline (for example, astronomy) if they were mutually compatible.

The materials processing payloads would be composed of equipment to do experiments in all promising areas of research; however, specific flights should be planned to emphasize experiments in individual areas such as biologicals, metallurgy, etc. It is anticipated that some of the payloads will require large amounts of electrical power (and corresponding thermal rejection), and it may be expected that additional power or thermal rejection kits will be required as part of the materials processing payload.

## Automated Materials Processing Kit Missions

Many materials processing experiments could be preplanned on the ground, carried out in space with a minimum involvement of the flight crew, and returned to earth for analysis. It is envisioned that such experiments could be prepared in the form of an automated materials processing kit which would include necessary support systems such as power or thermal rejection. This kit would remain in the Shuttle payload bay for the entire duration of the mission and would travel as a companion with another payload, such as an automated satellite to be deployed, or even a Spacelab. During a given portion of the Shuttle mission, the payload specialists would activate the experiments remotely from inside the orbiter and shut down the systems at the conclusion of the experiment runs. It is envisioned that such a kit would be available at the launch site and flown as frequently as payload bay volume, mission, or other constraints would permit (thus helping to optimize the utilization of the Shuttle). Plans should be made to include such a kit at least twice a year. The kit would probably be packaged in the shape of a cylinder about 4 meters (14 feet) in diameter (payload bay diameter) and about 2 meters (7 feet) in length.

## Carry-on Experiments

Plans should be made in the materials processing program to accommodate small carry-on experiments on a space-available basis on Spacelab missions. It is estimated that such carry-on experiments would weigh approximately 45 kilograms (100 pounds) and would require minimum electrical power and payload specialist involvement.

In comparing the above three types of materials processing missions with the existing Shuttle and Spacelab capabilities, no conflicts are found.

## Shuttle and Spacelab Flight Program Costs

Based on costs provided by NASA personnel, estimates have been made of funding requirements to carry out the recommended Shuttle and Spacelab flight programs and are shown in Table I. Launch costs are included. The total cost of the initial six-year flight program is estimated to be $240 million. Of this $240 million, approximately half is for launch costs and half is to build and operate the materials processing payloads and to fund principal investigators. It should be noted that the costs of NASA's ground-based materials processing program and the sounding rocket program are not shown on this table.

| ACTIVITY | COST PER FISCAL YEAR (in millions) | | | | | | | | | | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 | 1984 | 1985 | |
| SPACELAB MISSIONS | | | | | | | | | | | |
| Payload Equipment Development | 0.4 | 0.9 | 3.4 | 5.4 | 9.9 | 0 | 0 | 0 | 0 | 0 | 20.0 |
| Experimenter Support | --- | --- | --- | 1.0 | 2.8 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 28.8 |
| Operations and Maintenance | --- | --- | --- | 0.5 | 1.2 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 21.7 |
| Launch | --- | --- | --- | --- | 10.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 110.0 |
| | | | | | | | | | | TOTAL | 180.5 |
| AUTOMATED MATERIALS PROCESSING KIT MISSIONS | | | | | | | | | | | |
| Kit Development | --- | 0.5 | 1.5 | 3.0 | 5.0 | 0 | 0 | 0 | 0 | 0 | 10.0 |
| Experimenter Support | --- | --- | --- | --- | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 12.0 |
| Operations and Maintenance | --- | --- | --- | ---- | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 15.0 |
| Launch | --- | --- | --- | --- | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 12.0 |
| | | | | | | | | | | TOTAL | 49.0 |
| CARRY-ON EXPERIMENTS | | | | | | | | | | | |
| Payload Development and Experimenter Support | --- | 0.5 | 1.0 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 12.0 |
| Launch | --- | --- | --- | --- | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | | | | | | | | TOTAL | 12.0 |
| | | | | | | | | | | TOTAL | 241.5 |

Some data extrapolated from "Space Applications Program - 1974" NASA Headquarters, Washington, D.C., 1974, p. VI-29.

NASA R&D base and rocket program costs not included.

TABLE I APPROXIMATE COSTS OF MATERIALS PROCESSING SPACE FLIGHT PROGRAM

## Materials Processing R&D Base

The cost of NASA's ground-based research and development program on materials processing as currently planned (Reference 18) is approximately $3 million per year. In view of the fact that the Panel has recommended an aggressive applied space materials research program for the 1980's, and at the same time has felt that in several of the proposed research areas, the ground-based background work has been inadequate, the Panel has considered whether the level of effort in the ground-based program is sufficient. The R&D base must serve several functions including: provide analytical studies and ground-based experimental research on high-potential material systems (including model materials systems); develop new technology on space processing techniques, such as design of experimental space furnaces; provide cost and benefit studies on promising space-processing applications; provide consultant services with prominent scientists on an individual and group basis; support advisory panels to periodically and/or continually advise NASA in general and specific flight plans, etc. In summary, the R&D base is the foundation of the flight program and must serve as the instrument for identifying and evaluating original ideas and concepts for inclusion in the program.

> *The Panel recommends that NASA's R&D base program on materials processing be increased beginning in fiscal year 1976 from the anticipated $4 million per year to about $6 million per year and be maintained at that level each year thereafter. The Panel further recommends that in the formulation of this program each year, ideas be solicited from as wide a sector of the materials science community as possible.*

## SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

During its two weeks of intensive deliberations, the Panel on Materials Processing (which included in its membership some scientists and materials engineers who had previous experience in the program for processing materials in space and some members who had not) concluded that while the program is currently in an embryonic stage, there is a very high probability that substantial benefits will be derived from processing certain critical materials in space. These potential benefits cannot be confirmed or achieved, however, without preliminary exploratory research in space, complemented by extensive ground-based research.

Proposals for experiments which have been submitted to NASA to date are not viewed as necessarily an optimal selection. The Panel has, therefore, suggested a more limited selection of experiments which, in its view, have the maximum potential benefits for useful processing of materials in space, for leading to improved ground-based processing, and for increasing our knowledge of materials and processes. The experiments to be performed in space should be subject to careful review by members of the applied materials research community. The Panel believes that substantial savings in the program can be affected by discrimination in choice of experiments.

The Panel has identified a number of areas of materials processing of significant importance on earth which, in its opinion, are unlikely to be substantially affected by experiments in space, and these have been mentioned without detailed review of the considerable deliberations leading to these recommendations. For example, it seems clear to the Panel that space processing of *bulk, low-cost* materials will never be economically feasible. Furthermore, there are no current *manufacturing processes* (as distinguished from *materials processing*) for which the Panel has been able to identify a clear-cut advantage of manufacturing in the space environment.

### CONCLUSIONS

From its work in this study, the Panel on Materials Processing in Space has arrived at the following specific conclusions:

A vigorous and systematic research and development program is needed to define the potential human benefits from processes for separating, characterizing, and analyzing biomedical materials in the absence of significant gravitational forces.

Possibilities for separating several biomedical entities, each of benefit to thousands of patients, can be identified.

Of several conceptual processes, priority should be given to processing techniques that involve electrophoretic motion of living cells, biological complexes, and molecules through selected electrolytic solutions in electrical (and other) potential gradients.

The number of process variables is so large and in some instances so ill-defined that the design of definitive experiments is a very formidable task and will benefit from interdisciplinary effort and review.

It must be expected that the lead time to realize extensive potential socioeconomic benefits (except for possible significant demonstrations) will be more than 15 years. Early costs will probably be very large. Conventional cost-benefit analysis probably cannot be done usefully at this embryonic stage in our understanding of the effect of the space environment on the processing of materials.

Integration of space processing with pre- and post-flight procedures and policies requires such extensive interdisciplinary and interinstitutional arrangements that success of the proposed program is likely to bring about new disciplines and institutions.

During early stages of materials processing development in space, the design and conduct of definitive experiments will probably demand concentrating major support on one or two processes and products. Perhaps approximately one-half as much support (one-third of the budget for the program) should be reserved for intuitive and serendipitous research.

## RECOMMENDATIONS

It is apparent that during the past decades only a small fraction of the materials research community has been drawn into the program in materials processing in space or has even been aware of the opportunities. *The Panel recommends that NASA take the following steps to rectify this situation:*

> *A general review article on the current status of space experiments on materials should be written by a prominent member of the materials science community and published in a popular and widely circulated journal (such as Scientific American).*

*NASA should invite the Committee on Solid State Sciences of the National Research Council to devote one of its semiannual meetings to space-related materials research and engineering. This meeting should be held at one of NASA's Research Centers.*

*A standing Advisory Committee of prominent materials scientists should be formed to review progress in this field continuously and to make recommendations to NASA.*

*An outside peer group review system for evaluating proposals submitted to NASA (for example, in response to "Announcements of Flight Opportunities") should be adopted.*

*NASA should sponsor an annual conference to review progress in this field.*

A few key phenomena and systems have been selected as the most promising for future Spacelab studies using as criteria the impact upon basic science, the probability of being favorably influenced by a space environment, and the impact upon socioeconomic benefits. As previously indicated, the probability of cost effective exploitation of space processing for these individual areas cannot be quantitatively estimated at the present time. However, one must qualitatively characterize space processing as a relatively high-risk high-payoff area.

*It is recommended that program flexibility and objectivity be maintained for increasing or decreasing various aspects of the program as the Spacelab results of the future become available. It is deemed essential to have a competent and impartial review panel to assess the merits of specific aspects of the program. It should also be clearly established that, with the present assessment of space processing of materials, funding for this program should in no way compete with present and future research and development funds for nonspace research in materials.*

Clear definition of cost benefits related to the proposed program of space experimentation dedicated to applied research and processing in space is very difficult at this time because of lack of quantitative information. However, assuming successful accomplishment of the objectives reviewed in sections "Current User Needs," "Biomedical Applications," and "Processing of Inorganic Materials," it seems clear to the Panel that the magnitude of the impact, both in dollars and in beneficial effects for human life on earth, can be very high.

## REFERENCES


1. *Manufacturing Technology Unique to Zero Gravity Environment.* Conference held at NASA Marshall Space Flight Center, NASA-TM-X-62504. November, 1968.

2. *Space Processing and Manufacturing.* (Collected papers). ME-69-1. NASA Marshall Space Flight Center, October 21-22, 1969.

3. Bannister, T.C. *Heat Flow and Convection Demonstration (Apollo 14).* NASA TM-X-64735. NASA Marshall Space Flight Center, March 29, 1973.

4. McKannan, E.C., Krupnick, A.C., Griffin, R.N., and McCreight, L.R. *Electrophoresis Separation in Space: Apollo 14.* NASA-TM-X-64611, NASA Marshall Space Flight Center, August 29, 1971.

5. Yates, I.C., Jr. *Apollo 14 Composite Casting Demonstration.* NASA-TM-X-64641. NASA Marshall Space Flight Center, October, 1971.

6. Snyder, R.S. *Electrophoresis Demonstration on Apollo 16.* NASA-TM-X-64724. NASA Marshall Space Flight Center, November, 1972.

7. Bannister, T.C., Grodzka, P.G., Spradley, L.W., Bourgeois, S.V., Hedden, R.O., and Facemire, B.R. *Apollo 17 Heat Flow and Convection Experiments: Final Data Analyses Results.* NASA-TM-X-64772. NASA Marshall Space Flight Center, July 16, 1973.

8. Bredt, J.H. *New Space Processing Experiments for the Skylab Missions.* Paper presented at the 23rd International Astronautical Congress, Vienna, Austria, October 8-15, 1972. NASA Manned Space Center, Houston, Texas.

9. *Proceedings: Third Space Processing Symposium: Skylab Results.* Vol. I and II. Experiment 551: Metals Melting, p. 85; Experiment 552: Exothermic Brazing, p. 33; Experiment 553: Sphere Forming, p. 101; Experiment 479: Zero Gravity Flammability, p. 115; Experiment 556: Vapor Growth of IV-VI Compounds, p. 235; Experiment 557: Immiscible Alloy Compositions, p. 133; Experiment 558: Radioactive Trace Diffusion, p. 425; Experiment 559: Microsegregation in Germanium, p. 375; Experiment 560: Growth of Spherical Crystals, p. 257; Experiment 561: Whisker Reinforced Composites, p. 203; Experiment 562: Indium Antimonide Crystals, p. 275; Experiment 563:

Mixed III-V Crystal Growth, p. 301; Experiment 564: Metal and Halide Eutectics, p. 469; Experiment 565: Silver Grids Melted in Space, p. 159; and Experiment 566: Copper-Aluminum Eutectic, p. 457. NASA Marshall Space Flight Center, April 30-May 1, 1974.

10. Bannister, T.C. "Skylab Science Demonstrations," *Proceedings: Third Space Processing Symposium: Skylab Results.* NASA Marshall Space Flight Center, April 30-May 1, 1974.

11. *Preliminary Proceedings: Third Space Processing Symposium: Skylab Results.* Vol. I and II. NASA Marshall Space Flight Center, April 30-May 1, 1974.

12. *European Views on Processing and Manufacturing in Space.* European Space Research Organization, June, 1974.

13. American Institute of Biological Sciences, Panel on Electrophoresis in Space. Final Report on NASA Contract No. NASW-1901. June, 1974.

14. *Space Processing as Related to (1) Fluid Mechanics and Heat Transfer, (2) Containerless Processing, (3) Solidification of Metals and Semiconductors, (4) Preparation of Glasses and Ceramic Materials, (5) Electrophoretic Chemical and Biochemical Separation Processes.* Prepared for NASA under a grant to the Universities Space Research Association, NGR 47-102-003. April 15, 1974.

15. McCreight, L.R. "Use of Shuttle for Manufacturing and Materials Process Experiments in Low G." American Astronautical Society, Space Shuttle Payloads Session, Proceedings of the Symposium, December 27-28, 1973. *Science and Technology,* Vol. 30, 1973, pp. 211-230.

16. *Reference Earth Orbital Research and Applications Investigations.* NASA Handbook NHB 7150.1, January 15, 1971.

17. *Reference Earth Orbital Research and Applications Investigations, Materials Sciences & Manufacturing,* Volume 6. NASA Handbook NHB 7150.1, January 15, 1971.

18. *The Space Applications Program, 1974: The Space Processing Program.* NASA Office of Applications, Washington, D.C., May, 1974.

# BIBLIOGRAPHY

----------. *Abstracts: Third Space Processing Symposium: Skylab Results.* NASA Marshall Space Flight Center, Alabama, April 30-May 1, 1974.

----------. *Automated Space Processing Payload Equipment Study, Vol. 1-3.* Report on NASA Contract No. NAS 8-30741. Aerospace Systems Division, Bendix Corporation, Ann Arbor, Michigan, January, 1975.

Bloom, H.L., et al. *Study for Identification of Beneficial Uses of Space.* Final Report on NASA Contract No. NAS 8-28179, Phase I. Missiles and Space Division, General Electric Company, Philadelphia, Pennsylvania, December 10, 1972.

Bloom, H.L., et al. *Study for Identification of Beneficial Uses of Space.* Final Report on NASA Contract No. NAS 8-28179, Phase II. Missiles and Space Division, General Electric Company, Philadelphia, Pennsylvania, November 1, 1973.

Committee on the Survey of Materials Science and Engineering, National Research Council. *Summary Report: Materials and Man's Needs: Materials Science and Engineering.* National Academy of Sciences, Washington, D.C., 1974.

Frost, R.T., et al. *Electromagnetic Containerless Processing Requirements and Recommended Facility Concepts and Capabilities for Spacelab.* Final Report on NASA Contract No. NAS 8-29680. Space Sciences Laboratory, General Electric Company, Philadelphia, Pennsylvania, May 13, 1974.

Hammel, R.L. *Requirements and Concepts for Materials Science and Manufacturing in Space Payload Equipment Study.* Final Report on NASA Contract No. NAS 8-28938. TRW Systems Group, Redondo Beach, California, July, 1973.

Hammel, R.L., et al. *Space Processing Applications Payload Equipment Study.* Final Report on NASA Contract No. NAS 8-28938. TRW Systems Group, Redondo Beach, California, August, 1974.

----------. *The 1973 NASA Payload Model.* NASA Marshall Space Flight Center, Alabama, October, 1973.

----------. *Shuttle Sortie Payload Descriptions, Vol. II.* NASA Marshall Space Flight Center, Alabama, October, 1973.

----------. *Spacelab: An Orbital Laboratory for Science, Applications, and Technology.* European Space Research Organization, Neuilly, France, June, 1974.

----------. *Space Processing Applications Payload Equipment Study.* Interim Review Brochure on NASA Contract No. 8-28938. TRW Systems Group, Redondo Beach, California, April, 1974.

----------. *Space Shuttle Payload Planning Working Groups: Vol. 9, Materials Processing and Space Manufacturing.* Final Report, NASA TM-X-69459. NASA Goddard Space Flight Center, Greenbelt, Maryland, May, 1973.

----------. *Space Shuttle Program Review.* Brochure. NASA Johnson Space Center, Houston, Texas, June, 1974.

----------. *Summarized NASA/ESRO Payload Descriptions: Sortie Payloads.* NASA Marshall Space Flight Center, Alabama, October, 1973.

----------. *Summary of Space Processing Applications Payloads for Shuttle and Spacelab Missions.* Brochure. NASA Marshall Space Flight Center, Alabama, June, 1974.

Ulrich, D.R. et al. *Economic Analysis of Crystal Growth in Space.* Final Report on NASA Contract No. NAS 8-27942. Space Sciences Laboratory, General Electric Company, Philadelphia, Pennsylvania, July, 1972.

Veen, George E., editor and compiler. *Electrophoretic Separator Project M570.* Final Report on NASA Contract No. NAS 8-28365. Space Sciences Laboratory, General Electric Company, Philadelphia, Pennsylvania, September, 1972.