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Materials Processing in Space

Program Tasks

SUPPLEMENT

Compiled by Elizabeth Pentecost
Space Science Laboratory

National Aeronautics and Space Administration

George C. Marshall Space Flight Center

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16. ABSTRACT

This report is a supplement to the 1983 Materials Processing in Space Program Task catalog.[1] The purpose of this document is to provide an overview of the program scope for managers and scientists in industry, university, and government communities. The report is structured to include an introductory description of the program, its history, strategy, and overall goals; identification of the organizational structures and people involved; and a description of each research task, together with a list of recent publications.

The tasks are grouped into six categories: Crystal Growth; Solidification of Metals, Alloys, and Composites; Fluids, Transports, and Chemical Processes; and Ultrahigh Vacuum and Containerless Processing Technologies; Combustion experiments; Experimental Technology.

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NASA TECHNICAL MEMORANDUM

I. INTRODUCTION

The Materials Processing in Space program is directed toward research in the science and technology of processing materials under conditions of low-gravity to provide a detailed examination of the constraints imposed by gravitational forces on Earth. The program is expected to lead, ultimately, to the development of new materials and processes in commercial applications adding to this nation's technological base. The research studies emphasize the selected materials and processes that will best elucidate the limitations due to gravity and demonstrate the enhanced sensitivity of control of processes that may be provided by the weightless environment in space. Primary effort will be devoted to a comprehensive study of the specific areas of research which revealed potential value in the initial investigations of the previous decade. Examples of previous process research include growth of crystals and directional solidification of metals in the quiescent conditions in which gravitational fluid flow is eliminated, containerless processing of reactive materials to eliminate reactions with the container and to provide geometrical control of the product, synthesis and separation of biological materials in weightlessness to reduce heat and mass transfer problems associated with sedimentation and buoyancy effects, identification of high vacuum characteristics associated with an orbiting wake shield, and minimal knowledge of terrestrial processing methods.

Additional effort will be devoted to identifying the special requirements which drive the design of hardware to reduce the risk in future developments. Examples of current hardware studies are acoustic, electromagnetic and electrostatic containerless processing modules; and electrophoresis separation devices.

In addition to the basic research nature of the program, a lower level of effort is being expended on the business, a logistics and legal implication of rights of data and patents, control of materials, and division of responsibilities when NASA works with commercial ventures aimed at specific products. Examples of current materials research which might lead to commercialization include infrared detector crystals, inertial confinement fusion targets, electrolytes with dispersoids, aligned magnets, and ferromagnetic materials.

The current program emphasis on fundamental processing science and technology in selected areas will continue as the Materials Processing in Space program addresses problems of interest to the public and private commercial sectors which can be resolved by recourse to the space environment. During this phase of the program, the development and demonstration of current space technology for materials processing will be transferred, as appropriate, to non-NASA users. In order to assist this process, a Commercial Space Processing Task Team has been formed to resolve institutional constraints serving as disincentives to cooperative involvement. In addition, this team will serve as a single point of contact for interested parties and represent their interests within NASA.

Emphasis will be placed on the expansion of currently funded activities for ground-based and spaceflight investigations to maximize the outputs from these opportunities. Initiatives requiring new hardware will be encouraged at a low level until funds can be made available. The expansion of current efforts is occurring as a result of focusing support for current spaceflight investigations by forming facility experiment teams to provide advice and identify future involvement. Emphasis has been placed on experiments involving the Materials Experiment Assembly and Mid-Deck experiments on the Space Shuttle.

II. TASKS

1. CRYSTAL GROWTH

TASK NUMBER	PRINCIPAL INVESTIGATOR	SHORT TITLE
	Bachmann	Zone Leveling and Solution Growth
	Feigelson	The Influence of Low Frequency Vibrations
	Heeger	Improved Materials Preparation

Zone Leveling and Solution Growth of Complex Compound Semiconductor in Space

North Carolina State University
Dr. Klaus J. Bachmann
NAG1-354
May 1, 1983 - April 20, 1986

The objective of this program is to grow single crystals of $CdSnP_2$, $Cd_xHg_{1-x}Te$, $Ga_xIn_{1-x}Sb$ and InP_yAs_{y-1} by solution growth and zone leveling methods, respectively, for improved opto-electronic devices operating in the 1-5 μm wavelength region.

The program addresses the elimination of experimental difficulties in the growth of homogeneous III-V and II-VI alloy crystals and of incongruently melting ternary compound semiconductors that are caused by the deformation of the molten zone under the conditions of zone leveling at 1-g and that are due to buoyancy effects on the perfection, homogeneity and habitus under the conditions of solution growth. The program starts with a careful evaluation of the phase relations in the Cd, Sn, P system and the design of hardware for drop tower experiments concerning melt/container separation under the conditions of zone leveling at zero-g and for seed/melt positioning in the initial and final stages of solution growth. Ground-based research on the growth of $CdSnP_2$, $Cd_xHg_{x-1}Te$, $Ga_xIn_{x-1}Sb$ and InP_yAs_{y-1} crystals is carried out to optimize the growth conditions and to obtain insight into the combined effects of container interactions, vapor transport, diffusion layer instabilities and seed positioning on the perfection, homogeneity and habitus of crystals grown at 1-g. In the later phase of the program hardware for space experiments will be developed with the aim at improved crystals grown at 0-g and the fabrication of light sources and detectors operating in the near to intermediate IR wavelength region.

The Influence of Low Frequency Vibrations on the Growth of Single Crystals from Melts and Solutions

Center for Materials Research - Stanford University
Professor Robert S. Feigelson
NAS8-34872
July 6, 1982 - July 5, 1983

This program is concerned with the role of low frequency mechanical vibrations applied to liquids during crystals growth by the Bridgman method. Earlier work in our laboratory has shown that 60 Hz axial vibrations improved the quality of CdTe crystals grown by this method, but the mechanism for the decrease in dislocation density and in the incidence of polycrystallinity was unknown. Experiments with aqueous solutions have shown that 60 Hz axial vibrations do have a significant stirring effect but the stirring is not sufficiently rapid to change the crystal properties and we believe that the changes in crystal quality are caused by some interface mechanism. A novel and efficient stirring technique has been developed in which coupled vibrations are applied at right angles and in a horizontal plane. This technique appears to be the most effective yet devised for stirring liquids in closed containers and is considered an important subject for further investigations. The remainder of the present program will be devoted to studying the influence of this new mode of vibration on the crystal growth of CdTe.

Improved Materials Preparation, Role of Convection on Crystal Growth and Polymerization in One Dimensional Conductors and Conducting Polymers

University of California - Santa Barbara
Dr. A. J. Heeger
Dr. F. Wudl
NAGW-391
December 1, 1982 - November 30, 1983

The main objectives of this project are to obtain basic crystal growth information regarding electro-crystallization of organic metals and superconductors and fundamental information regarding electrolytic polymer film formation of organic polymeric conductors. This information will allow us to produce larger and better quality crystals as well as better films with improved electrical properties.

With this program we will determine the relative importance of electrochemical cell design, electrode materials, reactions at the counter-electrode(s), solvent polarity, current, and temperature. Specific experimental tasks will be crystal growth rate determinations as a function of variation of the above parameters. Results of crystal growth rates will be correlated with morphology and physical properties such as electrical conductivity, magnetic susceptibility, spectroscopy, etc. The same tasks will apply to electropolymerization where film growth rate and quality will be determined as a function of the above mentioned parameters. The materials to be investigated in this program will be tetramethyl-tetraselenafulvalene (TMTSF) salts, new donors, and polyheterocycles such as polythiophene.

2. SOLIDIFICATION OF METALS, ALLOYS, AND COMPOSITES

TASK NUMBER	PRINCIPAL INVESTIGATOR	SHORT TITLE
	Johnston	Solidification/Casting
	Stefanescu	Graphite Formation in Cast Iron
	Wallace	Solidification Fundamentals

Solidification/Casting

Marshall Space Flight Center
Dr. M. H. Johnston
Mr. R. A. Parr
Ms. W. A. Alter
In-House

The purpose of this program is to determine the influence of gravity on the grain structure and segregation of castings.

The metal-model ammonium-chloride and water was selected for the first series of flights since it solidifies with a structure similar to metals and is transparent so it can be photographed. Three metal alloys were selected for the second series. They were Sn-15Pb (large density difference between the elements), Sn-3Bi (experiences extensive dendrite remelting and fragmentation) and Al-4.5Cu (well-studied in literature, shows macrosegregation, and is the basis for the commercial 2000 series aluminum alloys). Progress to date includes: (1) columnar to equiaxed transition is convection dependent and does not occur in low-gravity; (2) dendrites coarsen more rapidly in low-gravity, resulting in larger arm spacings; (3) grain structure and dendrite arm spacings are more uniform in low-gravity; and (4) computer models can predict the trends but not the magnitude of segregation changes as a function of gravity. SPAR hardware will be used to solidify commercial aluminum bearing and free machining alloys (these contain the additional immiscible elements Bi and Pb).

Publications

Johnston, M. H. and Parr, R. A., "The Influence of Acceleration Forces on Dendritic Growth and Grain Structure," Met. Trans. 13B, 85 (1982).

Johnston, M. H. and Parr, R. A., "Low Gravity Solidification Structures in the Tin-15wt% Lead and Tin-3wt% Bismuth Alloys," in Materials Research Society Symposia Proceedings, Materials Processing in the Reduced Gravity Environment of Space, Volume 9 (G. E. Rindone, ed.), North Holland, 1982, p. 651.

Johnston, M. H. and Owen, R. B., "Optical Observations of Unidirectional Solidification in Microgravity," accepted for publication in Metallurgical Transactions.

Maples, A. L. and Pourier, D. R., "Convection in the Two-Phase Zone of Solidifying Alloys," accepted for publication in Metallurgical Transactions.

Graphite Formation in Cast Iron

The University of Alabama
Dr. D. M. Stefanescu
NAS8-34724
February 8, 1982 - June 15, 1983

The primary objective of this program is to study the solidification of cast iron by using a directional solidification furnace in conjunction with KC-135 aircraft flights allowing for investigation of sedimentation and convection in a low-gravity environment. The reasons for selecting cast iron as the material for this research are related to both theory and practice. Cast iron is one of the most complex materials used in modern technology. It can solidify with a normal lamellar eutectic (austenite-iron carbide), on abnormal lamellar eutectic (austenite-flake graphite) and a discontinuous eutectic (austenite-spheroidal graphite). When the stable path of solidification is followed resulting in a graphite eutectic rather than an iron carbide eutectic, the two phases of the eutectic, i.e., graphite and austenite, have remarkably different densities, making cast iron a most suitable material for the study of gravitational effects during solidification. From the practical standpoint, cast iron is the number one casting alloy and any theoretical gain could be translated in some improvement in the processing of this material.

The specific experimental tasks include directional solidification of commercial cast iron, pure Fe-C and pure Fe-C-Si alloys, on ground and flight experiments. Special emphasis will be put on cerium doped alloys with the purpose of obtaining spheroidal graphite. The quantitative correlations between composition (cerium content), the thermal gradient to the growth rate ratio, and the structure of commercial irons and pure Fe-C and Fe-C-Si alloys will be established. Some new fundamental scientific information on the crystallization of lamellar and discontinuous eutectics in general, and of cast iron in particular is expected to be the result of this effort.

Solidification Fundamentals

Case Western Reserve University
Professor J. Wallace
Dr. V. Laxman, Lewis Research Center
NAG3-417 (NASA Contact: Dr. H. R. Gray, Lewis)
March 10, 1983 - continuing task

The objectives of this program are to study "bulk undercooling" via containerless processing and macrosegregation mechanisms in high temperature alloys. A more complete understanding of these basic solidification phenomena may lead to possible new/improved earth-based solidification processes and alloys.

Initial baseline data on undercooling effects in pure Fe, Ni, and Fe-Ni alloys is being conducted with the cooperation of MSFC Drop Tube researchers (samples sent to MSFC 5/83). Characterization of samples and comparison with other data will provide guidance for future research. Preliminary designs for drop tower experimental capsules have been completed. Procurement and fabrication of a "macrosegregation capsule" and a "bulk undercooling capsule" are underway.

3. FLUIDS, TRANSPORTS, AND CHEMICAL PROCESSES

TASK NUMBER	PRINCIPAL INVESTIGATOR	SHORT TITLE
	Anderson	Cloud Microphysics
	Concus	Interfacial Phenomena
	Dressler	Suppression of Marangoni Convection
	Glicksman	Influence of Melt Convection
	Kohl	Theoretical Problems in Materials Science
	Sani	Thermo/Diffusocapillary Research
	Saville	Transport Processes Research

Cloud Microphysics

Marshall Space Flight Center
Dr. B. Jeffrey Anderson
Dr. M. T. Reischel, USRA
D. A. Bowdle, USRA
In-House

The objective of this program is to obtain an experimental verification of warm cloud formation theory by matching and verifying a numerical model of the experiment. The fundamental theory of cloud formation is believed to be well understood and accurately modeled, but it has been subjected to only very limited experimental verification. This experiment is designed to provide an improved experimental base by using a fundamentally new technique. This theory is basic to the understanding of cloud formation in the atmosphere and a variety of other processes (bubble formation in liquids, combustion, dual phase heat transfer). A correct understanding is critical to data interpretation for a variety of instruments (continuous flow diffusion chambers, cloud nucleus counters, aerosol counters).

The study is based upon thermal wave experiments in the KC-135 low-gravity environment. Cloud of droplets is formed and evaporated by a thermal perturbation transmitted by conduction through an air parcel. The location, as a function of time, of the cloud-clear air interface is compared to the model prediction. Several successful KC-135 flights have been made with result that model does not match experiment. Various problems with the model were resolved and improvements made. Second generation experiment hardware is nearing completion. A successful shake-down flight test of most of the new hardware was conducted in July.

Interfacial Phenomena

University of California-Berkeley
Dr. Paul Concus
Dr. Thomas L. Labus, Lewis Research Center
October 1, 1983 - September 30, 1984

The purpose of this program is to conduct reduced gravity research on interfacial phenomena related to various areas of materials science. Specific objectives of the research will be to experimentally determine the free surface shapes, pressure profiles, and temperature distributions for a variety of dynamic flows involving the competing influence of surface tension and viscous forces. Liquid-gas interfaces for reduced gravity fluid dynamics cannot be detemined experimentally on the earth. In addition, ground-based reduced gravity facilities are limiting in terms of available time, and steady state heat transfer effects are impossible to achieve. The work will include theoretical modeling, precursor experiments in drop towers, and the definition of Shuttle experiments.

Suppression of Marangoni Convection in Float Zones

George Washington University
Dr. R. F. Dressler

This is a program of both experimental and mathematical/computational research, related to the unwanted surface-tension convection which will always exist during float-zone processing in space. The experiments will focus upon demonstrating the validity and feasibility of our idea for suppressing Marangoni convection in float-zone processing of corrosive materials in space. Our experiments will be ground-based and will first use a material optically transparent, liquid at room temperatures, and non-corrosive, such as silicone oil. Our method consists of blowing suitably heated jet(s) of non-reactive gas over the free liquid surface to establish a total shear force equal and opposite to the force gradient which drives the Marangoni convection. We plan to start with a two-dimensional model with one free surface, then a model with two free surfaces; later we will try a cylindrical model, all models representing one-half of an actual float zone. The half chosen is that which is hotter on top than bottom, to suppress most of the complications of thermal convection in 1-g. The very small size of the liquid float-zone will also suppress most of the 1-g bulk effect compared with the surface effects. If our tests exhibit appreciable reduction in Marangoni convection, then plans and a design for a full float-zone experiment in space will be made. Successful results of such a test should instigate space application to the most important commercial cases such as silicon processing in space. Necessary computations will be made related to our experiments.

Influence of Melt Convection on Solid-Liquid Interfaces Under Terrestrial and Reduced Gravity Environments

Rensselaer Polytechnic Institute
Dr. M. E. Glicksman
NAG3-333 (NASA Contacts: Dr. H. R. Gray, Dr. A-T Chai, Lewis)
October 1983 - October 1985

The objective of this program is to determine the effects of gravitation on the morphology and kinetics of solid-liquid interfaces during constrained and unconstrained solidification. The interaction of convection with the transport fields for heat and solute during solidification has immense practical application. We have already discovered new forms of the convective interaction such as unexpected traveling waves at low frequencies, which may be especially important at low crystal growth rates. Probing the subtle effects induced by gravity is leading to deeper insight into solidification kinetics under terrestrial conditions also.

Model systems are being studied to probe the detailed effects that gravity induces on the morphology and kinetics of crystal growth. Plastic crystalline materials such as succinonitrile (body-centered cubic) and pivalic acid (face-centered cubic) are used to simulate metallic solidification with low and high surface energy anisotropy, respectively. Scaling laws have been devised to permit correspondences being established among the model systems and the real systems. This key step requires careful delineation of the relevant properties of the model system both with respect to solidification parameters and fluid flow parameters. In this manner, accurate model-system experiments can be used to obtain deeper understanding on rather difficult (real) systems undergoing similar processes. This approach has led to significant new discoveries in dendritic solidification and in convective interactions also.

Theoretical Problems in Materials Science

Institute for Theoretical Physics
Dr. Walter Kohn
NSFG PHY 77-27084

This program involves the study of theoretical physics in several disciplinary areas: condensed matters, pattern formation in solidification processes, physics of disorder and quantum noise in macrosegregation systems, soluble non-linear problems and their application, electronic structure of one-dimensional solids and the transport processes in one dimensional conductors. The use of a VAX 11/750 computer, made possible with this grant, will enable scientists to carry out needed data analysis for these experiments.

A proposed research program will also be concerned with problems of common interest to physicists and materials scientists. Materials problems have served as useful models in the investigation of fundamental theoretical questions. Examples include kinetics of phase separation, nonequilibrium solidification patterns, gauge theories of defects in crystals, etc. These are active areas of research at present. Other areas which might become comparably active involve kinetics of glass formation or nonequilibrium processes in polymeric materials. Another motive for this program is to provide an opportunity for the materials science community to participate more directly in the development of new analytic methods and to bring these methods to bear on problems of practical interest. Modern understanding of the kinetics of phase transitions, for example, has progressed to the point where it should be directly useful in the interpretation and control of metallurgical processes; but few metallurgists are prepared to work with these theories and few theoretical physicists have the motivation or practical background to make the detailed calculations that are needed for metallurgical purposes. Drs. J. W. Cahn, M. E. Glicksman, and J. S. Langer will bring together the necessary expertise to complement the interest of a comparable group of theoretical physicists.

Thermo/Diffusocapillary Research

University of Colorado
Dr. Robert Sani
Dr. Thomas L. Labus, Lewis Research Center
October 1, 1983 - September 30, 1984

The objective of this program is to conduct fundamental research on the effects of temperature and/or concentration driven convection. The resulting forces along interface, as well as motion in the liquid bulk, will be modeled analytically and experimentally verified. Specifically, the temperature and velocity profile in the vicinity of liquid-liquid and liquid-gas interface must be determined experimentally and compared with analytical models. Important questions regarding the onset of unsteady thermocapillary motion will be addressed. The program approach will include theoretical modeling, ground-based flight experiment definition utilizing the NASA LeRC 5 Second Drop Tower Facility and the conduct of related fluid dynamics and heat transfer experiments including a broad range of thermophysical phenomena.

Transport Processes Research

Princeton University
Dr. D. A. Saville
Dr. W. B. Russell
Dr. A-T Chai, Lewis Research Center
NAG3-447
July 14, 1983 - July 14, 1984

The objective of this effort is to conduct fundamental research in reduced gravity on transport processes occurring during crystallization and/or during solidification processes. The details of the transport processes in various materials processing modes will be systematically studied. A Shuttle experiment will be planned to provide a better understanding of the role of fluid motion on the formation of morphological patterns and roles of these patterns in solid composition. The approach to the research will involve theoretical modeling of transport processes, non-incursive ground-based laboratory measurements of model systems, and the definition of requirements for space experimentation.

4. ULTRAHIGH VACUUM AND CONTAINERLESS TECHNOLOGIES

TASK NUMBER	PRINCIPAL INVESTIGATOR	SHORT TITLE
	Barmatz	Multimode Acoustic Research
	Bayuzick	Studies on the Effect of Undercooling
	Doremus	Crystallization, Optical, and Chemical
	Flemings	Undercooling, Recalescence and Structure
	Perepezko	Solidification Fundamentals-Containerless
	Spaepen	Bulk Formation of Metallic Glasses
	Trinh	Undercooling and Nucleation Studies
	Uhlmann	Surface Active Elements in Glasses
	Weinberg	Glass Research

Multimode Acoustic Research

Jet Propulsion Laboratory
Dr. Martin Barmatz
NAS7-918
October 1, 1981 - September 30, 1984

The primary objectives of this task are to develop theoretical models of new classes of acoustic levitation and provide experimental validation of these models using research levitation devices.

There is a recognized need for high temperature containerless processing facilities that can efficiently position and manipulate molten samples in the reduced gravity environment of space. The ultimate goal of this research is to develop sophisticated manipulation capabilities in these geometries, such as selection of arbitrary axes of rotation and rapid sample cooling. This program will investigate new classes of levitation in rectangular, cylindrical and spherical geometries. The program tasks include calculating theoretical expressions of the acoustic forces in these geometries for the excitation of up to three acoustic modes (multimodes). These calculations are used to: (1) determine those acoustic modes that produce stable levitation; (2) isolate the levitation and rotation capabilities to produce more than one axis of rotation; and (3) develop methods to translate samples down long tube cylindrical chambers. Experimental levitators will then be constructed to verify the stable levitation and rotation predictions of the models.

Publications

Barmatz, M., Allen, J. A., and Gaspar, M., "Experimental Investigation of the Scattering Effects of a Sphere in a Cylindrical Resonant Chamber," JASA 73, 725 (1983). The associated theoretical analysis was performed at JPL by Dr. El Raheb and published in JASA 72, 1046 (1982).

Barmatz, M. and Collas, P., "Acoustic Radiation Force on a Sphere in Plane, Cylindrical and Spherical Standing Wave Fields," to be presented and published in Proceedings of 11th International Congress on Acoustics, July 19-27, 1983, Paris, France.

Studies on the Effect of Undercooling in a Low-Gravity Containerless Environment on the Structures and Properties of Alloys

Vanderbilt University
Dr. R. J. Bayuzick
NAS8-34676
May 1, 1983 - April 30, 1984

The objectives of this research are: (1) to clarify advantages and limitations of undercooling for the production of metastable phases in the Nb-Ge, Nb-Al, Nb-Sn systems where the A-15 phase has differing degrees of stability; (2) to evaluate, characterize, and understand the microstructures of Nb-Ge, Nb-Al, and Nb-Sn due to undercooling by drop tubes techniques; (3) to contribute to the understanding of the effect of microstructure on the superconducting transition temperature in A-15 structures; (4) to produce and maximize the superconducting transition temperature of bulk Nb_3Ge undercooling in a low-gravity containerless environment and; (5) to determine the maximum amount of undercooling possible for Nb base alloys containing Ge, Al, or Sn.

The first phase of this effort will focus primarily on the analytical work necessary to characterize, evaluate, and understand the microstructure of the Nb-Ge alloys, hence, during this period, much of the work to accomplish research objectives in the Nb-Ge system will be initiated. Simultaneously, Nb-Al and Nb-Sn alloys will be slowly phased in; however, the major effort involving the objectives for these systems will be relegated to the second phase of this effort.

Crystallization, Optical, and Chemical Properties of Fluoride Glasses

Rensselaer Polytechnic Institute
Dr. Robert H. Doremus
JPL-955870

The objectives of this program are to: (1) cooperate with JPL in constructing an ACES apparatus to prepare samples and experiments for space flight; (2) measure properties needed for the flight; and (3) examine the nucleation and crystallization kinetics of fluoride glass on the ground, so these properties can be understood and compared with results on containerless behavior.

Fluoride glasses have great promise as infrared optical components, especially fibers, because they are transparent to 8μ m and higher. In order to optimize properties, different glass compositions are needed. Some are hard to form in a container, and may possibly be formable in a containerless furnace. One goal is to understand crystallization behavior with and without a container, which should lead to glasses with optimum properties. Chemical durability (attack by water) is also an important property, which can limit or extend the applicability of fluoride glasses. Again improved understanding could lead to better durability and broader application as infrared optical components. The mechanism of reaction of fluoride glasses with water is being studied with nuclear reaction and Rutherford backscattering techniques of surface profiling, in cooperation with Professor W. A. Landford (SUNY-Albany).

Progress to date includes: (1) assembly of apparatus for melting fluoride glasses, melted and cast different compositions; (2) measurement of the thermal conductivity at room temperature; (3) measurement of the surface tension at 600°C by the frozen pendant drop method; (4) measurement of the crystallization kinetics with the differential scanning calorimeter (DSC) of different glass compositions; (5) examination of the morphology of crystallization in the light and scanning electron microscope; (6) cooperation with JPL in building the ACES in preparation for flight experiments; and (7) examination of nucleation theory.

Publications

Doremus, R. H., "Nucleation Theory: Is Replacement Free Energy Needed?" in Materials Research Society Symposia Proceedings, Materials Processing in the Reduced Gravity Environment of Space, Volume 9 (G. E. Rindone, ed.), North Holland, 1982, pp. 315-320.

Bansal, N. P., Doremus, R. H., Bruce, A. J., and Moynihan, C. T., "Kinetics of Crystallization of ZrF_4-BaF_2-LaF_3 Glass by Differential Scanning Calorimetry," J. Am. Ceram. Soc. 66, 233-238 (1983).

Bansal, N. P. and Doremus, R. H., "Surface Crystallization of a Fluoride Glass," accepted for publication in J. Am. Ceram. Soc., 1983.

Undercooling, Recalescence and Structure of Levitation Melted Samples

Massachusetts Institute of Technology
Professor M. C. Flemings
NSG-7645
October 1, 1982 - September 30, 1983

The objective of this program is to extend our fundamental understanding of the solidification of undercooled alloys through high speed optical measurement of temperature during recalescence after nucleation.

Work to be accomplished includes: (1) levitations of nickel, stainless steel, and nickel-tin alloys with and without glass slags; (2) development of thermal measuring instrumentation to reduce the response time from 100 μs to 10μ s; (3) measure recalescence behavior of various alloys; and (4) relate the measured recalescence behavior to metallographic structures observed.

Solidification Fundamentals - Containerless Processing of Undercooled Melts

University of Wisconsin-Madison
Professor J. H. Perepezko
NAG3-436 (NASA Contact: Dr. H. R. Gray, Lewis)
September 1, 1983 - August 31, 1984

The objective of this research is to understand the physical mechanisms controlling liquid undercooling and to apply this understanding to solidification processing methods. New insight into nucleation and crystal growth will be obtained in undercooled liquids of high melting point materials.

The droplet method will be applied to examine undercooled liquids processed in NASA drop tube and drop tower facilities as well as in a laboratory-scale apparatus. The processing parameters to be examined include melt superheat, droplet size and particle statistics, and droplet surface coating. Sample measurements will involve containerless processing conditions (i.e. temperature, pressure, etc.) and microstructural evaluation. Several alloys in iron and nickel-base systems have been identified for study. These materials were selected for their potential as high temperature materials.

Bulk Formation of Metallic Glasses and Amorphous Silicon from the Melt

Harvard University
Dr. Franz Spaepen
NAS8-35416
May 16, 1983 - May 15, 1986

This research is concerned with: (1) investigating the phase changes in liquid silicon droplets at large undercooling and exploring the feasibility of the formation of large masses of amorphous silicon from the melt; (2) characterizing the crystal nucleation and growth limitations of the formation of bulk metallic glasses from the melt; (3) characterizing the factors that influence the undercooling measured in droplet dispersions of pure metals; and (4) developing the atomistic understanding of transient crystal nucleation in a melt. The main experimental techniques to be used are solidification in either a 1 or 3 m drop tube and stationary solidification on nonnucleating substrate in vacuum after surface treatments. Characterization of the solidification products will be by calorimetry and microscopy.

Recent activity has been directed toward characterization of crystal nucleation in glass-forming alloys where the estimated homogeneous nucleation rate in some of these alloys seemed sufficiently low to allow them to be prepared in bulk glass form at slow cooling rates, if heterogeneous nucleation could be avoided. Containerless processing was used to eliminate one source of heterogeneous nucleation. Results tend to support the basic idea behind bulk glass formation in alloys with high reduced glass transition temperature. Also, results have indicated that containerless processing alone will not be adequate for producing bulk metallic glasses. Pretreatments to remove heterogeneous nucleants from the melt surface will be essential.

Plans include continuing investigation of the conditions for the formation of metallic glasses, with special emphasis on the problem of elimination of surface nucleants. This will be attempted by: (1) studying a variety of alloys with a high reduced glass transition temperature, and different surface chemistry; (2) coating of droplets with silicate as fluoride fluxes; (3) treatment of the droplet surfaces by gas phase reactions or vacuum evaporation oxides; and (4) containerless processing in larger drop tubes.

Undercooling and Nucleation Studies in Microgravity

Jet Propulsion Laboratory
Dr. Eugene H. Trinh
NAS7-918
April 1, 1983 - April 1, 1986

The principal objectives of this program are to utilize and to refine developed levitation and containerless materials processing techniques to conduct controlled solid-liquid phase nucleation experiments, and to carry out previously unavailable measurements of thermophysical properties of significantly undercooled metallic and organic melts. The results of this research will provide new information regarding the factors affecting the onset of the liquid-solid phase transition, as well as the properties of the undercooled melt ahead of an advancing freezing front.

The two fundamental tasks to be undertaken are the observation of the deepest undercooling achievable with freely supported liquid metals 0.1 to 2 mm in size as well as the factors affecting the premature nucleation onset, and the measurement of the physical properties (surface tension, density, compressibility, viscosity, specific heat) of the undercooled melts with non-invasive techniques. The investigations will make use of acoustic levitation facilities involving undercooled liquid drops suspended in both gaseous and liquid hosts. Inert gas environments will provde the media for levitating the substance of interest, and the controlled introduction of gaseous impurities or oxidizing agents together with the lowering of the temperature will allow the observation of the characteristics of heterogeneous, and perhaps homogeneous, nucleation phenomena. High boiling point polyphenyl oils and molten glasses will also serve as host media for levitation of undercooled immiscible drops. The surface tension (and the viscosity for moderately viscous substances) and its variations due to various surface active agents will be measured through drop oscillation techniques. Density and compressibility data will be gathered through acoustic levitation techniques. The measurement of specific heat will be attempted through radiative and microcalorimetric techniques. During the initial phase of this program levitation facilities will be used in the temperature range between -50 and +700°C. The materials under study will be among low melting metals such as gallium, tin, indium, aluminum, and various alloys, as well as glass forming organics such as O-terphenyl.

Publications

Trinh, E. and Apfel, R. E., "Sound Velocity of Supercooled Water Down to -33°C Using Acoustic Levitation," J. Chem. Phys. 72, 6731 (1982).

Trinh, E. and Wang, T. G., "Large Amplitude Drop Shape Oscillations," Proceedings of Second International Colloquium on Drops and Bubbles, NASA-JPL Publication 82-7, 1982, p. 143.

Trinh, E., Robey, J., Jacobi, N., and Wang, T. G., "A Dual Temperature Resonance Chamber: Applications to Acoustic Levitation and Materials Processing," to be presented and published in Proceedings of 11th International Congress on Acoustics, July 19-27, 1983, Paris, France.

Surface Active Elements in Glasses

Massachusetts Institute of Technology
Dr. D. R. Uhlmann
Dr. H. L. Tuller
NAGW-403
October 1, 1982 - September 30, 1983

The principal objective of this program is to characterize and explain the enrichment of glass surfaces in components which significantly lower the surface tension. The results should provide a quantitative basis for understanding the role of interfaces in fining glass, both on earth and in a microgravity environment, and should lead to improved control of lead migration in applications such as plasma panels where lead silicate glasses are employed as sealant materials.

The program is concerned with near-surface concentration profiles in glasses with elements such as lead, molybdenum and vanadium. These elements are known to have pronounced effect in lowering the surface tension; and surface enrichment is anticipated. The concentration profiles are being determined as a function of temperature in isothermal treatments as well as of thermal history for rate cooled specimens. Also being determined are compositional variations in the bulk due to density segregation and convection. The work is being carried out on lead silicate glasses, as well as lead, molybdenum and vanadium doped into borosilicate and soda-lime-silicate glasses. The principal technique being employed in this study is ESCA spectroscopy, although use is also being made of Auger spectroscopy and ion microprobe mass analysis. The surface concentrations are compared with bulk concentrations determined from in-situ fracture of the samples within the spectrometer. Samples with a range of relevant dimensions and hence relative likelihood of convective overturning are being explored. Once the experimental results are in hand, theoretical models will be developed to describe the experimental data.

Glass Research

Jet Propulsion Laboratory
Dr. M. C. Weinberg
NAS7-918

The overall objective of this program is to obtain both fundamental and practical information pertaining to the preparation and processing of glasses in a space environment. These studies will establish a quantitative scientific basis for containerless experiments with glass-forming materials.

The program is concerned with: (1) studying novel processes for glass formation that may be of particular value for the unique conditions available in space; (2) obtaining an understanding of the relationship of gel precursor preparation and drying procedure to the phase transformation characteristics of the gel-derived glasses in compositions of interest for space processing; (3) determining the applicability of classical homogeneous nucleation theory for predicting limiting glass compositions that can be prepared without crystallizing under space conditions; (4) investigating the factors that promote crystal nucleation at the glass surface; and (5) studying glass bubble formation and elimination in melts with and without the use of refining agents.

The primary activities toward these goals will be to: (1) determine the sequence of crystalline phase development in the surface crystallization of sodium disilicate glass and attempt to seek factors which abet such crystallization; (2) study the crystallization behavior of a four-component fluoride glass as a function of temperature and glass preparation procedure; (3) construct and test apparatus for performing glass bubble dissolution (growth) experiments, perform preliminary dissolution experiments, and compare experimental results with theory which we have developed; (4) initiate a study of the kinetics of the early stages of phase separation in a simple gel-drived glass; (5) develop procedure for preparing homogeneous gels and gel-derived glasses in a selected oxide system such as GeO_2-Pb_0 that are potentially important in the field of optical waveguide and IR applications; (6) compare the homogeneity of these gel-derived glasses with glasses of the same compositions prepared from the oxide mixtures; and (7) compare glass-forming ability due to differences in hydroxyl group and impurity concentrations.

Publications

Weinberg, M. C., Onorato, P.I.K., and Uhlmann, D. R., "Behavior of Bubbles in Glassmelts: I. Dissolution of a Stationary Bubble Containing a Single Gas," J. Am. Ceram. Soc. 63, 175 (1980).

Zak, M. and Weinberg, M. C., "Multibubble Dissolution in Glass Melts," J. Non-cryst. Solids 38 and 39, 533 (1980).

Weinberg, M. C., Onorato, P.I.K., and Uhlmann, D. R., "Behavior of Bubbles in Glassmelts: II. Dissolution of a Stationary Bubble Containing a Diffusing and Nondiffusing Gas," J. Am. Ceram. Soc. 63, 435 (1980).

Subramanian, R. S. and Weinberg, M. C., "The Role of Convective Transport in the Dissolution or Growth of a Gas Bubble," J. Chem. Phys. 72, 6811 (1980).

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Neilson, G. F. and Weinberg, M. C., "Anomalous Phase Separation Behavior of Gel-Derived Soda-Silica Glasses," in Materials Research Society Symposia Proceedings, Materials Processing in the Reduced Gravity Environment of Space, Volume 9 (ed. G. E. Rindone), North-Holland, 1982, p. 333.

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Weinberg, M. C., Neilson, G. F., and Smith, G. L., "Crystallization of Barium Fluorozirconate Based Glasses," J. Non-cryst. Solids, in press.

Weinberg, M. C., "Behavior of a Two-Component Gas Bubble in a Glassmelt with Chemical Reactions," Glass Tech. Ber., in press.

Subramanian, R. S. and Weinberg, M. C., "The Role of Surface Tension in Glass Refining," Glass Tech. Ber., in press.

5. COMBUSTION

TASK NUMBER	PRINCIPAL INVESTIGATOR	SHORT TITLE
	Berlad	Combustion of Particulate Clouds
	Pagni	A Fundamental Study of Smoldering
	Sirignano	Ignition and Flame Spread
	Strehlow	Flammability Limits of Gases Under Low-G
	Williams	Fundamental Studies of Droplet Combustion

Combustion of Particulate Clouds at Reduced Gravitational Conditions

State University of New York - Stony Brook
Dr. A. L. Berlad
NAG3-381
January 1, 1983 - December 31, 1983

The primary objectives of this investigation are to develop experimental apparatus, methodology, and theory for the characterization of flame propagation and extinction for uniform clouds of particulates under microgravity conditions.

Experimental efforts are concerned with establishing and using the scientific base required to carry out a family of experiments. Specific experimental tasks include the characterization of the dynamical forces acting on combustible particulates (e.g., lycopodium) in microgravity, methods of particle cloud mixing in closed volumes, ignition, and flame detection. The work is closely coordinated with related studies at NASA's Lewis Research Center and employs drop tower and other NASA facilities in the development and testing of experimental apparatus. The interpretation of expected microgravity combustion experimentation requires utilization of a theory of two-phase flame propagation and extinction. A suitable nonadiabatic theory is being developed as a major aspect of this program. These studies are designed to support the rapid development and utilization of a two-phase microgravity combustion experiment with results of broad and central interest. These efforts are in preparation for and support of a Space Shuttle-based combustion experiment.

Publications

Berlad, A. L., "Premixed Gaseous Flame Propagation and Extinction Limits," Progr. Astron. & Aeron. 73, 12 (1981).

Berlad, A. L., "Combustion of Particle Clouds," Progr. Astron. & Aeron. 73, 91-127 (1981).

Berlad, A. L., "Combustion Under Microgravity Conditions," AIAA/ASME 3rd Joint Thermophysics, Fluids, Plasma, and Heat Transfer Conference, St. Louis, MO, June 7-11, 1982, AIAA Paper 82-0880.

Berlad, A. L., "Fundamental Combustion Experiments in Microgravity," to be published in Proceedings of 4th European Symposium on Materials Sciences under Microgravity, April 1983, Madrid.

Berlad, A. L., "Multiphase Combustion Experimentation in Microgravity," to be presented at XXXIV IAF Congress, Budapest, October 1983.

A Fundamental Study of Smoldering with Emphasis on Experimental Design for Zero-G

University of California-Berkeley
Professor Patrick J. Pagni
Professor A. Carlos Ferandez-Pello
NAG3-443
October 1, 1983 - October 1, 1984

The key objective of this project is to identify key sets of low-gravity experiments which would critically compliment a larger set of more easily performed normal-gravity experiments to elucidate the phenomena found in smoldering combustion.

It is planned to follow through on the conceptual design of these experiments by participating in the future in the fabrication of the refined apparatus and in the actual data collection and interpretation. Low-gravity experiments are appropriate for smoldering combustion because of the complexity of smoldering which requires every means possible to discriminate among the many chemical and physical mechanisms operative in most smoldering combustion scenarios. The first year's efforts will be primarily analytical, attempting to identify appropriate approximations and dominant dimensionless groups based on existing data and state-of-the-art combustion modeling. Transient stability questions such as ignition, extinction and the choice among charring, tarring or flaming modes will be included.

Ignition and Flame Spread Above Liquid Fuel Pools

Carnegie-Mellon University
Professor William A. Sirignano
NAG3-404
February 1, 1983 - December 31, 1983

The main objectives of this project are to study phenomenon of ignition and flame spread above liquid fuel pools, and to determine factors that can improve fire safety. Dominant mechanisms for convective heat transfer and impact on ignition and flame spread above liquid fuel pools will be determined from these efforts.

The approach to be used is as follows: (1) analytical and computational study to evaluate scaling factors; (2) experimental design, development, and operation in laboratory at Earth's gravity; (3) experimental design for drop towers at NASA Lewis Research Center; (4) development and operation of drop tower experiments together with NASA Lewis personnel and; (5) develop recommendations for Learjet and/or Space Shuttle experiments. Through this research, a mathematical model of two-phase systems has been formulated and is being coded for the computer.

Flammability Limits of Gases Under Low-Gravity Conditions

University of Illinois-Urbana/Champaign
Dr. Roger Strehlow
NAS3-23770
September 30, 1982 - September 29, 1983

The main objective of this project is to determine the effect of gravity on the shape of the flame, its propagation speed, and its lean composition limits in a standard 2 inch diameter flammability tube. Premixed methane-air is the system that is being studied. This information will allow better understanding of the effect of gravity on flammability limits and therefore enhance our understanding of combustion safety in space.

At the present time a rig that contains eight flammability tubes on a rotating base has been constructed for mounting in the NASA Lewis Research Center's Learjet facility. It is planned that this jet will be flown under zero, fractional, and super-g conditions during an experiment in which a flame will be ignited and propagated through the tube. The 15 seconds of zero-g available in the Learjet facility will be adequate to study flame propagation through the entire length of the tube. The flame and digital g meters for the three orthogonal directions will be simultaneously photographed using high speed, high resolution film in a framing camera. The data will be analyzed to determine the effect of gravity on the propagation speed of the flame, the flame shape and the flammability limits in the methane-air system.

Fundamental Studies of Droplet Combustion at Reduced Gravity

Princeton University
Professor Forman A. Williams
NAG3-380
December 23, 1982 - December 22, 1983

The primary objective of this program is to ascertain how best to make use of reduced gravity to carry out scientific investigations of droplet combustion. In earlier work a preliminary conceptual design had been developed for droplet burning experiments for Spacelab. The present project concerns refinement of the earlier work with special consideration given to possible experiments for Mid-Deck Modules of the Space Shuttle.

The program involves a re-evaluation of suitable experiments on droplet combustion to ascertain whether influences of reduced buoyancy on time-dependent processes of heat and mass transfer in the gas or in the liquid, on extinction processes or on disruptive burning phenomena are best suited for further investigation. Components of the experimental apparatus, which include a droplet dispensing system, a droplet positioning system, a droplet ignition system and provision for recording, primarily photographically, the combustion of the individual droplet in a chamber having a controlled gas atmosphere, are being studied in an effort to determine optimal approaches to the experimental design. Methods for data reduction and interpretation are being made more specific, particularly in the context of an objective to calculate overall gas-phase chemical kinetic parameters for the combustion from observations of extinction conditions in different atmospheres. The work involves ongoing cooperative studies being performed at the NASA Lewis Research Center.

Publications

Williams, F. A., "Studies of Experiments on Droplet Burning at Reduced Gravity," to be published in Proceedings of 4th European Symposium on Materials Sciences under Microgravity, April 1983, Madrid, Spain.

6. EXPERIMENTAL TECHNOLOGY

TASK NUMBER	PRINCIPAL INVESTIGATOR	SHORT TITLE
	Aldrich	Development of MP Systems
	Owen	Advanced Optical Measurement Techniques
	Whymark	Acoustic Levitation Systems for MPS
	Williams	High Temperature, Controlled Redox System

Development of Materials Processing Systems for Use in Space on Low-G Simulation Devices

Marshall Space Flight Center
B. R. Aldrich
W. D. Whitt
In-House

The objective of this program is to continue to advance the state-of-the-art of materials processing systems for use in space. Materials processing systems will be designed for specific experiment requirements, prototype hardware built and tested to assure that all of the principal investigators requirements are met. Upon successful ground testing using the prototype system, flight hardware will be built.

Several furnace systems for use in space on low-g simulation devices have been developed for use on the drop tower and drop tube facilities that will process materials up to 1700°C. The General Purpose Rocket Furnace (GPRF) was developed for use in the Space Processing Applications Rocket (SPAR) Program. This furnace system was designed to accommodate a variety of experiments. It has flown several times, processing small isothermal and gradient samples during the SPAR program and on board the Shuttle as part of the Materials Experiment Assembly (MEA). Other furnace systems currently under development include: (1) the Advanced Automatic Directional Solidification Furnace (AADSF). A prototype of this furnace is currently being tested in the laboratory. Temperature gradients of over 900°C/cm have been achieved in this furnace by translating a thermocouple through an insulated quartz ampoule located in the furnace. The AADSF was designed modular, allowing major furnace components to be interchanged. In addition to re-arranging the major furnace sections, each furnace heating module can be easily removed and customized to accommodate a variety of specific experiment requirements from isothermal conditions to very steep gradients; (2) Heatpipe furnace, this will be based on the AADSF design and will utilize high temperature annular heat pipe to achieve long isothermal regions on either side of the gradient zone. The heat pipe will help to establish, along with other furnace components, very steep thermal gradients. Initially sodium-inconel heat pipes with a service temperature of up to 1100°C will be used. A program to qualify high temperature heat pipes for use in space will be undertaken.

Publications

Aldrich, B. R., "Furnace Systems Development," Proceedings of Third Processing Symposium: Skylab Results, Volume I, June 1974, M-74-5, p. 581-593.

Aldrich, B. R., "Space Processing Furnace Development," AIAA 15th Aerospace Meeting, Los Angeles, CA, January 1977, AIAA Paper

Aldrich, B. R. and Whitt, W. D., "Multipurpose Furnace for Research Rockets," U.S. Patent 4,158,742, June 19, 1979.

Aldrich, B. R. and Whitt, W. D., "Advanced Automated Directional Solidification Furnace," patent pending.

Aldrich, B. R., "Liquid Metal Heat Sink for Use in Space," Patent application filed, 1983.

Advanced Optical Measurement Techniques

Marshall Space Flight Center
Dr. R. B. Owen
W. K. Witherow
In-House

Optical measurement techniques are critical subsystems in several current and projected MPS experiments. This effort deals with the development and use of these techniques in the laboratory and under flight conditions to build the scientific and engineering base required for future flight experiments.

Advanced optical measurement systems suitable for MPS experiments are being developed in the labotatory. These systems utilize holographic, interferometric, schlieren, shadowgraph, and other optical techniques. Experimental optical systems are being built and flown on the NASA KC-135 low-gravity simulation aircraft to provide both engineering tests and scientific results in support of Shuttle MPS experiments. These optical measurement systems are being used on immiscibles, metal model, electrodeposition, and other materials in which convective flow is an important part of the process to gain understanding of low-gravity fluid behavior, nucleation and separation, and other processes. As a particular example, to collect the data for Ostwald ripening a holographic microscopy system and a sophisticated isothermal temperature control system were developed and built. Experiments have been and are being conducted to collect data on diffusional growth, coalescence, Stokes flow, Marangoni flow, and Ostwald ripening. From this data a computer model will be made.

Publications

Owen, R. B., "Interferometric Measurements of Unidirectional Solidification in Microgravity," JOSA 72, 1762 (1982), Abstract.

Witherow, W. K., "Holographic Microscopy Studies of Emulsions," NASA Tech Brief, 1982.

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Johnston, M. H., Owen, R. B., and Shurney, R. E., "Optical Observations of Unidirectional Solidification in Microgravity," NASA TP-2110, January 1983.

Owen, R. B. and Witherow, W. K., "Dual Laser Optical System and Method for Studying Fluid Flow," U.S. Patent 4,391,518, July 5, 1983.

Presentations

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Witherow, W. K., "Holographic Observations of Ostwald Ripening," presented at Solidification Working Group Meeting, Huntsville, Alabama, May 16-19, 1983.

Acoustic Levitation Systems for MPS

Intersonics, Inc.
Dr. R. R. Whymark
Dr. C. Rey
NAS8-33742
November 1979 - September 30, 1983

The objective of this program is to develop and fabricate flight hardware systems capable of performing experiments to attain containerless melting and solidification of a wide range of materials. Acoustic levitation is difficult at high temperatures. Adequate heating rates, processing times, and cooling rates must be obtained and contamination must be controlled. The importance of nucleation processes, mixing, and fining of glasses in low-g environments is still not understood.

Development and perfection of a fully automated experimental apparatus including a multiple specimen injector and retrieval system, acoustic positioning system, and using a state-of-the-art hot wall high temperature furnace, a cold wall very high temperature heating system, and a pressure acoustic levitation system for ground research will be achieved. Progress to date has included: (1) drop tower verification of acoustic levitator at moderately high temperatures; (2) successful KC-135 tests of basic acoustic levitator system up to 1500°C; (3) partial success of SPAR VI flight; (4) successful containerless melting on SPAR VIII flight; and (5) improved specimen stability achieved in 1-g ground-based levitator.

High Temperature, Controlled Redox Acoustical Levitator System

Johnson Space Center
Dr. R. J. Williams
Dr. G. E. Lofgren
In-Center
October 1, 1982 - September 30, 1983

The objective of this effort is to design, develop, and test a high temperature acoustical containerless melting system in which oxidation-reduction conditions can be controlled, freely manipulated, and measured. The work will be focused on the production of a laboratory prototype and test of that prototype with iron-bearing silicate melts. The objective will be approached by a combination of in-house and contracted research. We will contract the development of a prototype levitator, furnace, and enclosure, and the definition of basic operating characteristics. Our in-house work will involve the design and construction of the gas mixing, control, and monitoring system. We will perform the integration and the testing and evaluation of the system.

Techniques for containerless melting have developed substantially during the last ten years. The techniques have enormous value to materials science because they eliminate container/sample interaction. Consequently, contamination of samples by container material and corrosion of containers by samples can be minimized. Also, phenomena related to homogeneous nucleation can be better studied with such a system. Containerless melting will find its biggest use in manufacturing activities in space where the weightless environment allows relatively large samples to be levitated at high temperatures. Advances in technology of single-axis, acoustic systems allow terrestrial use of such systems on relatively dense (1-2 mm spheres of density 3 materials) temperatures of 1000°C. Projected technology development suggests that temperatures of 1200-1600°C will be achievable within a year. In this year we will complete a design feasibility study to further determine whether such a system can be built.

APPENDIX A
MPS ORGANIZATIONS

MPS ORGANIZATIONS

Alabama A&M University
Huntsville, AL

Battelle Columbus Laboratories
Columbus, OH

Bjorksten Research Laboratories
Madison, WI

Carnegie-Mellon University*
Pittsburgh, PA

Case Western Reserve University*
Cleveland, OH

Clarkson College of Technology
Potsdam, NY

EG&G Corporation
Santa Barbara, CA

French Atomic Energy Commission
Nuclear Research Center of Grenoble
Grenoble Cedex, FRANCE

S. H. Gelles Associates
Columbus, OH

General Electric Company
Space Sciences Laboratories
Valley Forge, PA

George Washington University*
Washington, D.C.

Grumman Aerospace Corporation
Bethpage, NY

Harvard University*
Cambridge, MA

NASA
Headquarters
Washington, D. C.

Institute for Theoretical Physics
University of California
Santa Barbara, CA

Intersonics, Inc.
Northbrook, IL

Iowa State University
Ames Laboratory, ERDA
Ames, IA

Jet Propulsion Laboratory*
Pasadena, CA

NASA*
Johnson Space Center (JSC)

KMS Fusion, Inc.
Ann Arbor, MI

NASA
Langley Research Center (LaRC)
Hampton, VA

Lehigh University
Bethlehem, PA

Lockheed Corporation
Huntsville Research & Engineering Center
Huntsville, AL

Massachusetts Institute of Technology*
Cambridge, MA

Michigan Technological University
Houghton, MI

Midwest Research Institute
Kansas City, MO

NASA*
George C. Marshall Space Flight Center (MSFC)
Marshall Space Flight Center, AL

McDonnell Douglas Corporation-East
St. Louis, MO

National Bureau of Standards
U. S. Department of Commerce
Washington, D.C.

National Bureau of Standards
Boulder Laboratories
Boulder, CO

North Carolina State University*
Raleigh, NC

Northwestern University
Evanston, IL

Ohio State University
Columbus, OH

Pennsylvania State University
University Park, PA

Princeton University*
Princeton, NJ

Rensselaer Polytechnic Institute (RPI)*
Troy, NY

Rice University
Houston, TX

Science Applications, Inc. (SAI)
Huntsville, AL

Semtec, Inc.
Huntsville, AL

Stanford University
Stanford, CA

State University of New York-Stony Brook
Stony Brook, NY

University of Alabama, Huntsville (UAH)

University of Alabama, Tuscaloosa
University, AL

University of Arizona
Tucson, AZ

University of California-Berkeley

University of California-Santa Barbara

University of Colorado
Boulder, CO

University of Houston
Houston, TX

University of Illinois at Urbana-Champaign
Urbana, IL

University of Missouri-Rolla
Rolla, MO

University of Oregon
Health Sciences Center
Portland, OE

University of Rochester Medical Center
Rochester, NY

University of Sydney
Sydney, AUSTRALIA

University of Utah
Salt Lake City, UT

University of Wisconsin - Milwaukee

University of Wisconsin - Madison

Westech Systems, Inc.
Phoenix, AZ

*These institutions and organizations have new contracts with the National Aeronautics and Space Administration (NASA).

APPENDIX B
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APPROVAL

MATERIALS PROCESSING IN SPACE PROGRAM TASKS
Supplement

Compiled by Elizabeth Pentecost

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

A. J. Dessler
Director, Space Science Laboratory

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