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PROCEEDINGS OF THE WORKSHOP ON AN ELECTROMAGNETIC POSITIONING SYSTEM IN SPACE

The Summary of a Meeting Held May 1-2, 1978, at NASA Headquarters, Washington, D. C.

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ABSTRACT

A workshop was convened at NASA Headquarters, Washington, D. C., on May 1 and 2, 1978, to help determine if sufficient justification existed to proceed with the design of an electromagnetic (EM) positioning device for use in space. Those in attendance included experts in crystal growth, nucleation phenomena, containerless processing techniques, properties of materials, metallurgical techniques, and glass technology.

Many of the scientists present perceived a need to conduct containerless experiments in a microgravity environment. Specific areas mentioned included the study of metallic glasses and investigations of the properties of high-temperature materials. Although the scientific requirements for the experiments were discussed only in general terms, they indicated a desire for some of the capabilities inherent in an electromagnetic system (e.g., positioning in a vacuum).

The potential usefulness of an EM positioning system for use in a microgravity environment was agreed upon. The discussion indicated that extensive ground-based studies (both theoretical and experimental) are necessary to ascertain the advantages of such a system and to optimize a design suitable for experimentation in space. These ground-based studies would also include precursor experiments on facilities such as drop tubes which offer limited times of low-gravity environment.

As a result of the discussions it was decided that those scientists who have a potential use for a microgravity EM positioning system would form an ad hoc task team and meet periodically to:

(1) Better define the requirements for the microgravity facilities.

(2) Oversee any design/development efforts associated with a microgravity EM facility.

(3) Make recommendations on developing technologies/facilities which support ground-based research efforts. These support activities may include developing facilities to conduct precursor experiments (e.g., on KC-135 flights) or measurement capabilities (e.g., multicolor pyrometers) needed to instrument any facility.

ACKNOWLEDGMENTS

The editor would like to thank Dr. R. Bunshah, Professor D. Turnbull, Dr. A. Witt, Dr. J. Margrave, Dr. D. Das, Dr. L. Lacy, and Dr. T. Frost for their help in preparing this document.

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I. THE WORKSHOP

This document summarizes a workshop held at NASA Headquarters on May 1 and 2, 1978. The motivation for the workshop was to determine if there was sufficient scientific interest and justification to proceed with the design and development of an electromagnetic (EM) positioning/furnace device for use in an Earth orbital microgravity environment. A list of those attending the workshop is given in the Appendix. Several presentations were given which involved topics dealing with techniques of containerless processing, research areas that utilize containerless processing, and other related subjects. Table 1 lists the presentations.

TABLE 1. WORKSHOP PRESENTATIONS

Title	Speaker
The Materials Science in Space Program and Participation of Investigators in Its Activities	J. Carruthers
Properties of Liquid Metals at High Temperatures	J. Margrave
Thermophysical Properties of Molten Nonconductors	J. Colwell
Corrosive Reactions in Oxides	H. Parker
Surface Tensions of Reactive High Temperature Materials	S. Hardy
Production of Bulk Metallic Glasses in Space	A. Lord
Studies of Immiscible Materials	A. Markworth
Potential for Ultra Purification of Metals	R. Bunshah
Research Activities at RADC	R. Marshall
Containerless Processing of Rare Earth Magnetic Materials	D. Das
Potential Problems Associated with Electromagnetic Levitation in Crystal Growth	A. Witt

TABLE 1. (Concluded)

Title	Speaker
Effect of Static Electric and Magnetic Fields on Material Processes	T. Collings
Use of Levitation and High Vacuum Techniques in Nucleation	D. Turnbull
The NASA/MSFC Drop Tube Facility	R. Naumann
Studies of Crystal Growth in an Electromagnetic System	G. Wouch
Characterization Studies of an Acoustic Levitator	W. Oran
Limitations and Potential for Electromagnetic Containerless Processing	T. Frost

The presentations were discussed in some detail. The research areas of interest to the attendees appeared to be grouped into four general categories; namely, properties of high-temperature materials, nucleation studies and the production of amorphous metals, production of unique metals and alloys, and EM systems and crystal growth.

The state of the research in these various areas was debated to some extent. It was stated that many experiments conducted in these areas are adversely influenced by the 1-gravity environment. For example, measurements of the physical properties of materials should be made in a containerless (e.g., levitated) manner. It is very difficult to obtain a complete set of data on the thermophysical properties of many materials, especially when they are in the molten state, because of crucible reactions for many of the materials. Crucible interactions can be avoided by use of electromagnetic levitation techniques, but conventional terrestrial levitation techniques do not lend themselves to suitable control of specimen temperature and cause considerable superheating of most high-density materials. The formation of metallic glasses and related studies of nucleation also appear limited by container effects, such as induced nucleation from the crucible walls. In the case of the production of oxygen-free, high-purity samarium-cobalt alloys (for the manufacture of magnetic materials of high coercivity), space offers a possible advantage in the initial preparation of the samarium-cobalt alloy in a containerless vacuum system. An EM facility might also be used in other experiments in space. An example is its use for controlled heating in a float zone apparatus. (Additional discussion of the research areas can be found in Section II.)

It was pointed out that there must be quantitative studies of the limitations of containerless processing systems in a 1-gravity environment to justify conducting investigations in microgravity. In the case of EM levitation systems there appears to be a wide range of material and temperature combinations that cannot be investigated on the ground. Other techniques which may be used on the ground include the acoustic systems being developed at various laboratories [e.g., Jet Propulsion Laboratory and Marshall Space Flight Center (MSFC)] and the high-speed calorimetry presently being developed by the National Bureau of Standards. In the case of terrestrial acoustic levitation systems, one of the major limitations may be disruption of materials in the liquid state when subjected to the intense sound fields being generated in the system. In addition, the processed materials will pick up impurities from the gas, making it virtually impossible to process high-purity materials. In the case of high-speed calorimetry, current-induced instabilities and surface tension effects of materials in the liquid state may adversely affect the measurements. (Additional information on containerless processing systems can be found in Section III.A.)

Many of the workshop participants explicitly expressed concern about the apparent limitations of containerless processing systems in a 1-gravity environment. They indicated a desire to conduct containerless experiments in a microgravity environment to remove some of the limitations. In addition, the capabilities inherent in an EM system (which can combine the effects of levitation, vacuum, and stirring) appear to be required to conduct some of these experiments. The potential utility of an electromagnetic positioning/furnace system for use in a microgravity environment was agreed upon. (Initially, this system should be used as a research facility to study basic physical processes in microgravity.) However, the necessary ground-based studies are not sufficiently matured that the need of an EM system for the Spacelab/Shuttle can be definitely established. Therefore, to justify and develop a system for use in Spacelab, an integrated program which includes the following elements should be established:

(1) Sufficient ground-based research, including use of terrestrial containerless systems so the advantages of conducting microgravity experiments on the Shuttle/Spacelab (or equivalent) can be firmly established.

(2) The ground-based research should include microgravity experiments of short duration (e.g., with drop tubes or the KC-135 aircraft) to fully justify the need for conducting experiments in Earth orbit. (A brief description of the MSFC 30-m drop tube is provided in Section III. B.)

(3) Sufficient ground-based research to design the space experiments, design the hardware, and analyze the results obtained with a space experiment.

(4) Close cooperation between the scientific groups that will use the apparatus and the engineering teams that are designing the space facility.

(The latter element is particularly important because of the NASA budgetary cycle. It generally requires 5 years from the initiation of budget requests for a facility to the time when flight experiments can be conducted. Because of the general advancement of science, these flight experiments will probably not be identical with those conceived initially and which generated the impetus for the facility. Close cooperation and periodic re-examination of requirements are essential to insure that the final flight hardware can be used to conduct the desired experiments.)

II. POTENTIAL RESEARCH AREAS OF CONTAINERLESS PROCESSING

A. Properties of High-Temperature Materials

Knowledge of the basic thermophysical properties of high-temperature materials is fundamental to the field of material science. Quantitative values of parameters such as melting points, vapor pressures, and specific heats are necessary in engineering systems design. In another area, data on the variation of surface tension with temperature would be useful to assess the potential influence of Marangoni flows in some processes (e.g., Czochralski growth).

Some of the most serious problems in determining the thermodynamic properties of molten materials arise from the necessity of holding the molten sample in a container in conventional calorimetry or vaporization studies. For example, liquid metals at high temperatures

(~ 1500° C) are very reactive systems, and it is usually impossible to find a container material which is sufficiently refractory and truly nonreactive. Therefore, until recently, only limited experimental data were available for liquid metals, and for metals melting above 2000° C all of the data were estimated. The compilations of thermodynamic data were based on estimates of specific heats and heats of fusion, and recent experiences[1] have shown that these can be very inaccurate.

When the furnace of the conventional drop calorimeter was replaced by a radio frequency induction heating coil, one could levitate samples of liquid metals in the coil and thus eliminate the container problem. Measurements of the heats of fusion and specific heats have been made for many of the transition metals (e.g., titanium, nickel, cobalt, platinum) using RF levitation devices at Rice University. These experiments have in many instances identified some of the limitations of conventional terrestrial RF levitators. Superheating of the specimen is perhaps the most severe limitation associated with terrestrial systems. This can be compensated to some extent by introducing ultrapure gas which can cool the material. However, there are still experimental difficulties such as: (1) a metallic "smoke" which can surround the levitated melt and complicate temperature measurements, and (2) vapor from the metal which can condense and short out the coils and hence limit the range of measurements. This latter difficulty is most severe in the case of high vapor pressure materials such as chromium, which cannot be heated much above the melting point in present EM systems. Many of these difficulties can be eliminated by conducting these experiments in a microgravity environment where an EM system with widely spaced coils can be used to position the specimen. Heating of the material can then be done in a manner independent of the positioning force (e.g., with an electron beam).

Another limitation of terrestrial devices is the current inability to levitate poor conductors (e.g., boron and carbon) and many of the nonconducting inorganic compounds (e.g., sulfides, borides, carbides, or organic compounds). There is considerable interest in determining the properties of refractory components such as the binary transition metal oxides and various ternary compounds, e.g., the alkali oxides/transition metal oxides. Compositions in the K_2O-Fe_2O_3 system which

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1. See, for example, A. K. Chaudhur, D. W. Bonnell, L. A. Ford, and J. L. Margrave: High Temperature Science, Vol. 2, 1970, p. 203.

include the β-alumina structure types are of special interest because of their potential application in MHD systems and as electronic/ionic conductors. Alkali oxide and transition metal oxides are, in general, so reactive that studies of phase equilibria are severely hampered and major uncertainties introduced in fixed point determinations (e.g., melting points) by sample-container reaction.

Finally, by conducting high-temperature, containerless experiments in space where there is a better control of variables, the syntheses of unique substances (e.g., silicon suboxides, silicon dihalides) could be studied in a systematic manner. Such species are already known to yield thin films of highly pure silicon (polycrystalline) when they are disproportionate.

B. Nucleation Studies and the Investigation of Metallic Glasses

Investigations of nucleation processes are important in themselves and also in the context of metallic glass formation. The technological promise of glassy metals as soft magnetic, structural, or corrosion-resistant materials has been pointed out in a number of papers.[2] At present, Allied Chemical is producing a composition known as Metglass 28-26 ($Fe_{40}Ni_{40}P_{14}B_6$) for use in transformer cores, magnetic shields, and other applications. The Metglass 28-26 appears commercially valuable because material with the desired "soft" magnetic properties can be produced in one process, unlike some of the standard materials (permalloy) which require several somewhat costly heat treatments.

There is a definite need for systematic study and characterization of crystal nucleation processes in glass-forming alloys. The conditions for the occurrence of homogeneous nucleation should be established, and the frequency of homogeneous nucleation in one or more of those glass-forming alloys in which it is observable should be measured. Such experiments should establish, among other things, the ultimate limits of undercooling which can be sustained by bulk specimens at moderate cooling rates. The most critical evaluations of this limit would be provided by containerless, vibration-free (to eliminate dynamic nucleation)

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2. See, for example, D. Turnbull: J. Electronic Materials, Vol. 4, 1975, p. 771.

experiments under high vacuum. These are conditions which could best be realized in zero-gravity experiments. It is believed that homogeneous nucleation might be reached if container nucleating effects were eliminated and reactive gases which form solid nucleating films on the metal surface were removed.

Processes for putting metallic alloys into bulk glass form at moderately slow cooling rates would be useful to study. (Samples larger than a few millimeters in the smallest dimension are not presently available.)

It is generally known that nonmetallic melts with reduced glass temperatures $T_{rg} = T_{glass}/T_{mp}$ exceeding 2/3 generally can be undercooled in bulk to the glass state at very slow cooling rates. Indeed, there is no evidence that homogeneous crystal nucleation ever occurs in such systems. It may be possible that metal glasses with $T_{rg} > 2/3$ would behave similarly if container effects and heterogeneous nuclei could be completely eliminated. However, metal melts are more susceptible to heterogeneous nucleation than are nonmetal melts.

Large samples of metallic glasses are desirable to obtain statistically accurate values of the mechanical (e.g., yield point) and elastic properties as well as to assess how much of the size dependence there is in these properties. Present indications are that alloys having the largest T_{rg} can be best produced in bulk. Therefore, one is interested in characterizing the crystal nucleation behavior of $Pd_{82}Si_{18}$-based alloys which have T_{rg}'s of 0.55 and higher.[3] The resistance of these alloys to crystallization is known to increase[4] with partial substitution of Cu or Au for Pd.

$Pd_{775}Si_{165}Cu_{06}$ is presently being contemplated for use in a containerless processing experiment or a rocket flight. These data would help characterize the production of bulk metallic glasses in a microgravity environment as contrasted to those produced on Earth. One of the results of these studies could be an assessment of the importance of the

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3. H. S. Chen and D. Turnbull: Acta Met., Vol. 17, 1969, p. 1021.

4. H. S. Chen: Acta Met., Vol. 22, 1974, p. 1505.

surface-to-volume ratio and the cooling rate on nucleation. No systematic work in this area has yet been generated; however, some laboratory work is now being conducted at Harvard University.

It would also be valuable to study the homogeneous crystal nucleation behavior of pure molten metals. Several investigations have indicated that a number of pure molten metals may be capable of sustaining reduced undercoolings approaching that exhibited by Hg without appreciable crystal nucleation. However, in none of these experiments was the occurrence of homogeneous crystal nucleation systematically investigated or demonstrated. Therefore, it is desirable to investigate thoroughly the crystal nucleation behavior of droplets of some of these metals (e.g., Ni, Cu, Au, or Pb) out of contact with supporting surfaces and free of surface films. These conditions can be approached most nearly in a gravity-free system. Principally, one would determine the ultimate undercooling of the pure molten metals and the grain structure which develops when crystallization is initiated at undercoolings near the ultimate.

C. Production of Unique Metals and Alloys

1. Cobalt-Samarium Magnetic Material. Typical coercivities in sintered $SmCo_5$ magnets are found to be in the range of 15 to 30 kOe. The highest value recorded for the room temperature value of coercivity in a sintered product is 43 kOe. Plasma-sprayed Sm-Co magnets have been produced with intrinsic coercivities as high as 67.5 kOe.[5]

Although the preceding values of coercivities realized in the Sm-Co magnets are far superior to those in any other magnet, they are still far short of the theoretical maximum attainable with this material. The theoretical maximum value of coercivity is derived from the magnetocrystalline anisotropy of the $SmCo_5$ crystal. If a $SmCo_5$ magnet composed of crystallites without any defects can be produced, it may be possible to reach an intrinsic coercivity of 350 kOe. This high coercivity may be used in such areas as: (1) precision accelerometers and gyroscopes, (2) d.c. motors of great reliability and versatility to compete against electrohydraulic devices, and (3) alternators for aircraft.

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5. K. Kumar, D. Das, and E. Wettstein: High Coercivity, Isotropic Plasma Sprayed Samarium-Cobalt Magnets, 23rd Conference on Magnetism and Magnetic Materials, November 9-11, 1977, Minneapolis, Minnesota; J. Appl. Phys., Vol. 49, No. 3, Part 2, 1978, p. 2052.

It is now well accepted that reversal in sintered Sm-Co occurs by a process of nucleation of reverse domains at defect sites in a crystal at low fields and then propagation of the reverse domain through the crystal by a sweeping of the domain wall with comparative ease. The defects can be surface irregularities, lattice distortions caused by foreign atoms, oxide particles, microcracks, etc.

The larger the number of defects in a crystal, the more likely it is to reverse at a lower field. Therefore, if we could develop a procedure for making rare earth-cobalt magnets which are composed of defect-free crystallites, we should not only be able to produce magnets with zero irreversible loss, but also those that have highly stable performance at elevated temperatures. This should result in a magnet with an intrinsic coercivity approaching 350 kOe and in by-products of near-zero irreversible loss and extremely high stability.

So far we have discussed the reversal of magnetization at fields much smaller than the anisotropy field and have stated that the defects in the crystals were responsible for the mechanism. A major and known cause of these defects is the presence of oxygen in the material, and a suspected cause is the presence of contamination acquired from the container vessel during the melting of the Sm-Co alloys.

Research recently conducted at the Draper Laboratory has provided strong evidence of the damaging influence of oxygen on the coercivity and the coercivity-retaining ability of a samarium-cobalt magnet. The oxygen content in sprayed magnets is less (by an order of magnitude) than is found in a commercial sintered magnet. Sprayed magnets also have almost twice the coercivity. In addition, these magnets are greatly resistant to degradation from thermal processing that is known to be severely detrimental to commercial magnets. This increased coercivity-retaining ability is believed to be directly related to the lesser amount of oxygen in the material.

To produce magnetic materials of low oxygen content, one should develop alloy melting and solidification techniques in a high-vacuum, containerless system to produce contamination-free ingots. One would then have to comminute the ingot and encapsulate fine powders of these alloys without contamination. This might be accomplished in a high-vacuum or ultrapure inert gas atmosphere. Densification of the powder compacts will be carried out by conventional techniques without exposure to air or by hot isostatic pressing, which appears very promising. In general, one desires densification to the theoretical maximum without grain growth and prolonged homogenization at densification temperatures.

2. Immiscible Alloys. Experiments have been proposed to examine the structure of liquid phase immiscible alloys (e.g., aluminum-indium) produced in the absence of gravity and to explore the possibility of producing immiscible alloys of unique properties. It has been speculated that difficulties associated with some of the flight experiments have resulted from nonhomogenization of the melts before solidification. One of the methods by which the segregation problem may be reduced is to melt the specimens in an EM facility where the stirring resulting from the strong currents produced in the material could homogenize the materials.

3. Ultrapure Metals. Many of the properties of metals are determined by the presence of impurity atoms and imperfections (point defects, such as vacant lattice sites, interstitial atoms, dislocations, etc.). Moreover, there is considerable interaction between impurity atoms and imperfections influencing an extensive array of physical, chemical, and mechanical properties. The effect of trace impurities on properties is attributed to such factors as lattice binding, electron mobility, mobility of atoms and point defects, movement of dislocations, mobility and properties of grain boundaries, and nucleation of phases. An example of this interaction between impurities and imperfections is shown by the observation that ARMCO iron (600 ppm impurities) will take up 50 cm^3 of cathodic hydrogen per 100 grams, whereas zone refined iron will take up only 2.3 cm^3 per 100 grams. The interaction between impurities and dislocation generation and movement in bcc metals has been well documented. The highest purity metal (1 ppm impurity) has an impurity content of $10^{16}/cm^3$. If one can succeed in lowering the impurity content of pure metals by a factor of 10^2 to 10^3, one might expect markedly different properties.

One method of purifying metals is a two-step process: vacuum melting followed by vacuum distillation and condensation of the vapors on a heated clean substrate to produce a fully dense deposit.

Space offers some potential advantages for conducting this type of experiment that are not readily obtainable on the ground. For example, using an EM device to position the initial charge can reduce container-induced impurities.

4. Metastable Peritectic Superconducting Compounds. The intermetallic superconducting compound Nb_3Ge has scientifically interesting and technologically useful properties since it has the highest known superconducting transition temperature of 23 K. Previous skull melting studies indicated that the compound is crystallographically unstable at high temperatures and decomposes into the compound Nb_5Ge_3 and a distorted A-15 peritectic phase. More recent splat cooling and thin film preparation techniques, such as cosputtering and codeposition of the elemental vapors, have shown that the compound exists as an ordered A-15 crystallographic phase that is metastable. At present, no one has prepared and studied metastable Nb_3Ge in bulk form, although such samples would be of important scientific value since the present thin film forms have not allowed detailed physical property measurements, such as neutron diffraction experiments, to be made on the material.

Previous attempts to obtain bulk forms of the material by casting have failed for a variety of reasons that are not reviewed here. It is expected that crystalline samples of A-15 metastable Nb_3Ge can be prepared if sufficient undercooling can be achieved in the molten alloy. As shown by Turnbull and others, a quiescent containerless environment is ideal for achieving large amounts of undercooling. Therefore, a containerless low-gravity environment, which may be achieved in space, could be used for preparing such metastable crystalline materials.

D. Electromagnetic Systems and Crystal Growth

1. General Considerations. One of the primary advantages of materials processing in space lies in our ability to operate in a containerless mode. Since activities in space appear unavoidably associated with residual gravity and incremental gravity variations, it is necessary that systems such as metallic melts (including semiconductor melts) be stabilized in predetermined positions. Such stabilization can in principle be achieved through acoustic and/or electromagnetic means. Given the fact that convection-inducing body forces are significantly increased in the case of EM stabilization, it might be concluded that acoustic stabilization techniques are to be preferred. There are instances, however, where EM levitation appears preferable.

One of the inherent liabilities of crystal growth conducted in a containerless mode lies in the fact that a multitude of minority constituents in the melt (which are expected to be uniformly incorporated in the solid) exhibit a high vapor pressure and, therefore, evaporate during containerless processing. This evaporative loss—an asset as far as purification of one-component systems is concerned—results, under convection-free diffusion-controlled conditions, in both radial and longitudinal compositional variations in single crystals obtained by liquid-solid phase transformations.

Containerless processing in space is, moreover, subject to radial heat transfer (radial heat loss from the solid formed) which in turn leads to curved growth interface morphologies and, consequently, to radially nonuniform segregation. EM systems may be effective through direct coupling with the solid produced in compensating for radial, radiative heat losses and thus in reducing the radius of curvature of the solidification front.

In view of the attractive features of EM stabilization and heating, it is strongly suggested that all effects of EM stabilization, heating, and body forces on metallic melts and solids be extensively investigated. Should the previously discussed conditions be realizable, EM stabilization and heating devices may provide the means to achieve controlled liquid-solid phase transformations in which the resulting solid matrices exhibit compositional homogeneity on both a micro- and macroscale.

2. Crystal Growth. Present techniques of preparing single crystals of high melting temperature alloys and compounds by floating zone crystal growth do not appear to have produced compositionally homogeneous single crystals.[6] Very high melting temperature refractory metal carbide single crystals, such as those of tantalum carbide and hafnium carbide (melting temperatures of 3900° C), to our knowledge, have not been produced at all in sizes of 5 mm or larger. Crystals of vanadium carbide produced by float zone in 10 atmospheres of helium to reduce evaporation loss contain as much as 0.1 percent by weight of oxygen and nitrogen as well as other impurities. Although these crystals were relatively large (8 cm long and 1 cm in diameter), homogeneity throughout was not attained. Better techniques of preparing single-crystal carbide materials appear desirable.

In terms of better preparation of these carbide single crystals and other high melting temperature crystals discussed previously, the tech-

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6. R. G. Lye, G. E. Hollox, and J. D. Venables: "Bonding, Structure and Mechanical Behavior of V. C. Single Crystals," from Anisotropy in Single-Crystal Refractory Compounds, Vol. 2, Plenum Press, New York, 1968.

nique of levitated solidification in a microgravity environment may offer certain advantages. These are: (1) freedom from contaminating surfaces and (2) rapid melting and crystallization which prevents changes in stoichiometry due to evaporation of constituents over long periods of time.

The technique of liquid encapsulation has been used in the growth of compounds with a high dissociation vapor pressure. For example, gallium phosphide crystals have been grown in a pressurized system where the melt is under a liquid layer of B_2O_3. However, the requirements for the encapsulating liquid generally restrict the material that can be used. Using such a liquid container for crystal growth in a microgravity environment could remove some of the restrictions on the material. For example, typically the encapsulating liquid is of lower density than melts. Also, the relative contact angles of the encapsulant and melt with the container determine whether or not a good seal is obtained. Such restrictions are removed in a weightless environment and may allow for the growth of compound materials not easily obtainable on Earth. In addition, melt shaping may be performed (e.g., using containers with CaF_2 encapsulated Si melts) which allows crystals with controlled cross sections to be grown.

III. CONTAINERLESS PROCESSING SYSTEMS

A. Potential Capability and Limitations of Containerless Processing Systems

Electromagnetic systems have been used for several years to successfully levitate and heat metal systems in a 1-gravity environment. (Bunshah has made an excellent review of the topic.[7]) The advantages of this type of system are well recognized and include: (1) no crucible contamination, (2) rapid homogenization of the melt, and (3) rapid rates of heating and melting. However, there are some fundamental disadvantages with these terrestrial systems—namely: (1) difficulties in attaining and controlling the desired temperatures, (2) high vaporization losses which can result in shorting of the coils, and (3) dynamical instability problems with large charges (> 20 grams)—which appear to make it

7. R. F. Bunshah: "Melting, Casting, and Distillation Techniques which Minimize Crucible Contamination," Chapter 18, Part 2, Vol. 1, Techniques of Metals Research, ed. R. F. Bunshah, Interscience Publishers, 1968.

impossible to melt and hold them for long periods of time.

The characteristic problem with metals in terrestrial devices is that they are heated to hotter temperatures than desired in order to levitate. The temperature attained by a small specimen in a vacuum when levitated at low frequencies is given by

$$T^4 = \left(\frac{7 \cdot 10^9}{8\pi} \frac{g}{\sigma}\right)\left(\frac{\rho_m \rho_e}{\epsilon a}\right)\left(\frac{B^2}{\text{grad } B^2}\right)$$

$$= \begin{pmatrix}\text{universal}\\ \text{constant}\end{pmatrix}\begin{pmatrix}\text{specimen}\\ \text{properties}\end{pmatrix}\begin{pmatrix}\text{facility}\\ \text{property}\end{pmatrix}$$

where

T = absolute temperature
g = gravitational acceleration
σ = Stefan-Boltzmann constant
ρ_m = specimen density
ρ_e = specimen electrical resistivity
ϵ = specimen emissivity
a = specimen radius
B = average magnetic induction

[CGS units except ρ_e in Ω-cm]

As is seen from the preceding equation, the specimen temperature is proportional to $(1/a)^{\frac{1}{4}}$; therefore, increasing the size of the specimen can reduce its temperature to some extent. However, this is true only up to a point. For large specimens (weight > 2 grams in one instance[8]) the temperature of the specimen will again increase. This is due to the fact that a large specimen extends beyond the region in the coil where the field is most favorable to lifting, and there is additional heating generated for a given lifting force. Some of the problems of overheating samples can be eliminated by immersing the system in a pure helium or hydrogen atmosphere. Additional cooling can be attained when the gas is flowed by the sample, although at the higher flow rates turbulence can be induced with some frequency near a resonant frequency of the sample.

Perhaps the most serious limitation of EM systems is their inability to levitate poorly conducting materials in a 1-gravity environment

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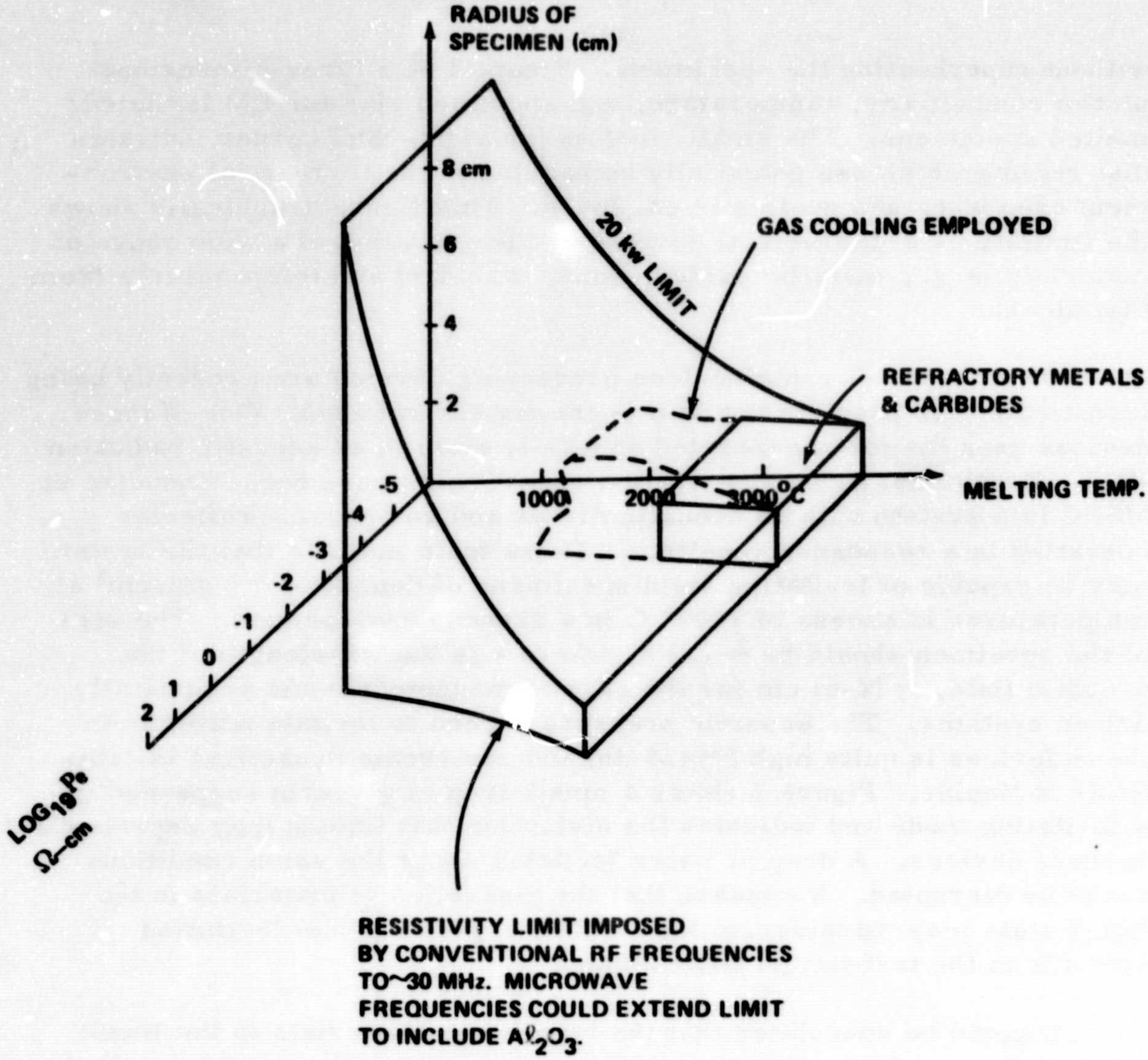
8. Bunshah, op cit.

without superheating the specimens. Figure 1 is a three-dimensional plot of conductivity, temperature, and specimen size for EM levitated/melted specimens. The small block in the right-hand corner indicates that regime which can potentially be handled in the terrestrial environment even when gas cooling is employed. This figure graphically shows the limitations of terrestrial devices by the exclusion of a wide range of materials (e.g., metallic oxides, some carbides) and temperatures from that block.

Other types of containerless processing devices are presently being investigated for possible use in a 1-gravity environment. One of these devices uses the force generated on a body when in an acoustic radiation field. Preliminary characterization experiments have been conducted at MSFC in a system with an acoustic driver and an opposing reflector operating in a resonance condition. These tests indicate that the system may be capable of levitating solid specimens of densities ~ 5 gm/cm^3 at temperatures in excess of 1000° C in a gaseous environment. The size of the specimen should be $\lesssim 1/3\ \lambda$, where λ is the wavelength of the acoustic field, $\sim$ (2-6) cm for the case of magnetodynamic acoustically driven systems. The acoustic pressure needed to levitate material in these devices is quite high ($\sim$ 165 db) and can create dynamical instabilities in liquids. Figure 2 shows a small drop of glycerin suspended in a levitating mode and indicates the distortion that liquids may experience in these devices. A drop of water levitated under the same conditions would be disrupted. It appears that the disruption of materials in the liquid state may characterize the limitation of acoustical levitation systems in the terrestrial environment.

It could be speculated that the behavior of materials in the liquid state could also determine the limits of other types of systems presently being developed for terrestrial application. For example, the high-speed calorimetric system currently being developed at the National Bureau of Standards has been used to measure the properties of solid materials. When used with materials in the liquid state, the heating currents may induce instabilities in the liquid (analogous to the pinch and kink instabilities which have been a problem in some plasma studies). These instabilities, in addition to surface tension effects, could complicate measurements.



The principal limitation of terrestrial levitation techniques is the lack of means of specimen temperature control. Such control can, however, be furnished in a limited fashion for materials of extremely high melting temperature or by use of inert gas cooling. This regime of limited control is indicated only semiquantitatively since it depends specifically upon specimen density, resistivity, tolerance to contamination by inert gas flow, as well as the cooling rate required for the experiment.

Figure 1. Limits of terrestrial levitation melting and solidification techniques using electromagnetic systems.

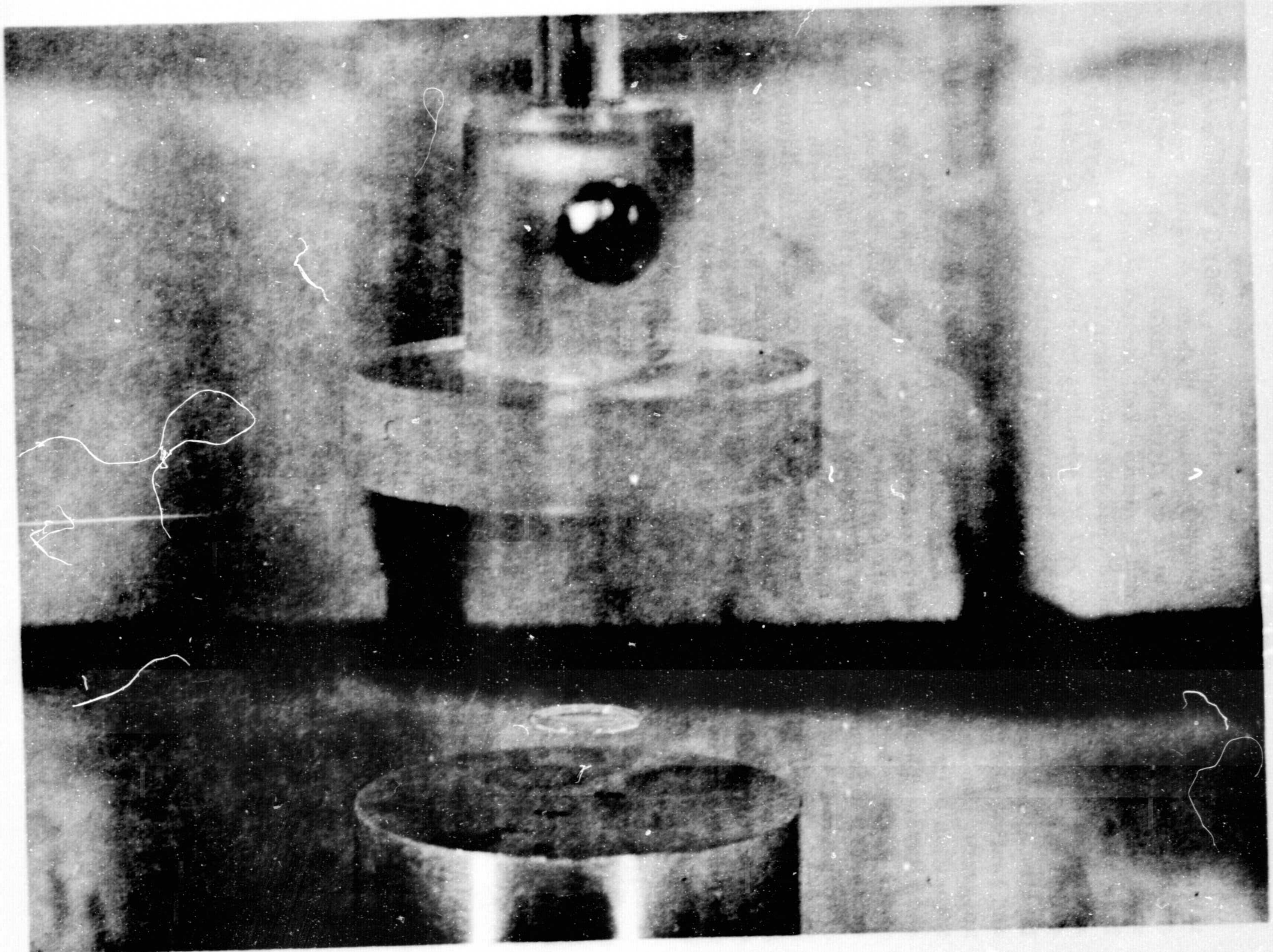


Figure 2. A 3 mm drop of glycerin levitated in a single-axis acoustic levitator. The intense sound fields have modified its original spherical shape.

B. Containerless Drop Tube Solidification Studies

A drop tube apparatus has been developed at MSFC to study containerless calorimetry and solidification of high-temperature reactive melts. The drop tube apparatus consists of a high-vacuum (10^{-6} torr) drop tube 31.5 m in length and a vacuum bell jar assembly. A containerless melting apparatus, based upon the pendulant drop technique, is installed in the stainless steel bell jar which is located directly over a 4-inch i.d. stainless steel tube. Instrumentation and viewing ports are located at intermediate levels (every 20 ft). Since both the temperature and heating power of the sample can be monitored simultaneously, the apparatus can be used as a containerless calorimeter to determine phase transition points, specific heats, and heats of fusion of reactive metals and alloys. The pendulant drop technique also allows for a determination of the surface tension of reactive melts. The apparatus has been used successfully to melt a variety of metals and alloys up to the melting point of tungsten (3410° C), with most of the present work dealing with Nb and Nb alloys (melting temperature 1900° C to 2470 ° C) with drop diameters in the range of 1 to 5 mm. The amount of undercooling in molten drops can be determined by using streak photography. Undercooling in excess of 350 K has been observed in pure Nb and in excess of 450 K for selected Nb-Ge alloys.

Because the present apparatus relies on radiation cooling, this technique works well only for metals and alloys with solidification temperatures in the range of 1500° C or higher. The system is presently being modified so that He gas may also be used for cooling. With this modification, the system will consist of an EM levitator to heat and suspend the samples and a secondary source of heat which will consist of a focused lamp or CO_2 laser. This modification should extend the capabilities of the hardware to study containerless heating and cooling of a variety of materials, including metallic glasses and immiscible alloys.

APPENDIX

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APPROVAL

PROCEEDINGS OF THE WORKSHOP ON AN ELECTROMAGNETIC POSITIONING SYSTEM IN SPACE

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The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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