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TITLE- Uses of Manned Space Flight for Materials Science and Processing in Space

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ABSTRACT

An earth orbiting manned space station will provide important new capabilities for the pursuit of research and development activities in the general field of materials technology. Skilled men in a weightless environment can investigate materials and processes which are difficult or impossible to produce on earth. Material refining and crystal growth are particularly attractive areas for investigation. Other interesting possibilities include novel structural materials, and a number of unique forming processes.

While practical applications can be envisioned for many of the processes examined, an extensive research and development program would be required before commercially valuable products could be produced on a significant scale. The initial emphasis should be upon research to understand zero gravity processing and the unique material properties which can result rather than upon attempts to manufacture specific products.

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PREFACE

The following Technical Memorandum was written in preparation for and support of a study conducted by the Science and Technology Advisory Committee (STAC) of NASA's Office of Manned Space Flight on The Uses of Manned Space Flight, 1965-1985. This study was held December 6-9, 1968 at La Jolla, California. The ideas expressed have been developed largely through discussions with scientists and engineers in a number of fields. Particular thanks are due Dr. W. G. Shepherd of STAC. The responsibility for the statements made, however, rests with the present authors.

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DATE: March 21, 1969

FROM: M. H. Skeer
L. D. Sortland
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TM-69-1015-3

TECHNICAL MEMORANDUM

I. INTRODUCTION

New materials, and new processes for producing, refining, and fabricating them, are essential to our technological progress. The purpose of this paper is to examine the possibility of exploiting unique features of the space environment for further progress in these areas. Specifically, we shall speculate on the possible utilization of a manned space station in the period beyond 1975 to carry out research and development in the general area of materials technology.

It is assumed in this study that a substantial manned space station program will be in operation, and that men, materials, equipment and power can be made available for appropriate investigations in orbit. We ask whether worthwhile materials research and development activities can be identified and, if so, which types of activity are most likely to prove fruitful. Investigations in this area are usually exploratory in nature, with many trials and many failures. Often, the most valuable results are completely unexpected. Skilled men in an orbiting laboratory should be able to carry out whole programs of experiments which would be prohibitively expensive and time consuming to carry out unmanned.

Despite the great importance of materials technology and the enormous amount of research devoted to the subject, a systematic program for carrying out such research in space has received relatively little study. A number of general qualitative surveys have been presented at meetings devoted to practical space applications (1-3), and proposals have been made for individual experiments in such related fields as

Physics, Advanced Technology and Engineering Operations. Recently, however, Marshall Space Flight Center (MSFC) has initiated a program to identify and evaluate candidate processes for space manufacturing (4-6). These efforts have been primarily directed toward applications, but extensive developmental research is clearly required before specific products can be achieved.

Our objective in the following sections is to discuss the most promising new processes and materials and to make a preliminary evaluation of their future potential. At present we can only speculate on what the eventual applications will be.

II. PROPERTIES OF THE SPACE ENVIRONMENT RELEVANT TO MATERIALS AND PROCESSING

We first consider the properties of the environment which may lead to new processes and applications. In this respect, the one unique characteristic is the phenomenon of weightlessness, usually referred to as zero-g. This is the only factor which cannot be duplicated on earth, although such features as the large volume of vacuum may be difficult or costly to produce. The principal characteristics of the earth-orbit environment are summarized below.

A. The Gravitational Field

It is important to recognize that zero-g does not mean literally zero gravitational force in orbit, but rather an approximate balance between the gravitational and centrifugal forces. All free-floating objects have independent orbits and will generally contact a container wall within one orbit, unless an external force is applied to prevent this. Other sources of disturbance include crew motions, mechanical and acoustical vibrations, attitude-control and orbit-keeping maneuvers, and atmospheric drag.

The required constraining force in all cases is quite small and accelerations of 10^{-5}g or less should be maintainable for extended periods of time. Accelerations during peak station maneuvers and crew activities, however, may increase to 10^{-2}g. A more detailed discussion of the zero-g environment is presented in the Appendix.

B. The Space Vacuum

The level of vacuum in low earth orbit is considerably poorer than the 10^{-13} to 10^{-14} torr currently achieved in vacuum chambers on earth. For comparison, mean atmospheric pressures for several representative altitudes are given below (7).

Altitude, km	Naut. Miles	Static Pressure, torr
150	81	3.8×10^{-6}
300	162	1.4×10^{-7}
700	378	8.9×10^{-10}
>2500	1350	$<10^{-12}$

These values are lower limits on the attainable vacuum pressure, since spacecraft leakage will contaminate the environment. Calculations on predicted leak rates for the Apollo CM or LM indicate that the effective pressures will be as high as 10^{-5} torr within a few meters of the leak source (8).

On Earth, back contamination resulting from low pumping rates and small volumes is often a limiting factor in vacuum chamber performance. This would not be a constraint in free space where much larger flow rates could be achieved. Vacuum technology is advancing rapidly, however, and by the time space processes requiring large volumes of good vacuum become feasible, earth capabilities for vacuum pumping may be competitive with earth orbit both in pumping rates and cost.

C. Radiation Environment (Ref. 9)

The high energy and particle radiation environment does not appear to provide any particularly useful characteristics because fluxes are too low and are subject to random fluctuations. Temperatures on the order of 5000°K, difficult to obtain using normal heat transfer methods, can be attained with solar reflectors.

III. OPPORTUNITIES PROVIDED IN ZERO-G

A number of unique processes have been suggested for possible study and application in the space environment. Lists of these processes have been given by Wuenscher (5), Frost (10) and Steurer (11).

In zero-g, density variations become unimportant and convection currents are suppressed. Variable density mixing of immiscible liquids and liquid/solid/gas suspensions is achievable. Support of bodies is unnecessary, so that contact distortions and impurities can be avoided. Vibrations can also be effectively isolated.

It is difficult to gage the potential impact of specific processes for products which would be otherwise unavailable or impractical to manufacture in the earth environment. Some applications are immediately recognizable but others, of perhaps far more reaching consequences, remain yet to be discovered. The following sections summarize and review the most promising of the processes proposed. Specific applications are cited only as representative examples of potential use.

A. Improved Crystallographic or Microscopic Properties of Materials

Levitation by RF fields on earth, the closest long term simulation of zero-g, has shown great promise but suffers from basic limitations of being restricted to conducting materials and to small quantities. Moreover, the supporting forces are concentrated near the periphery where induced eddy currents are maximum. In zero-g, these processes can be extended to nonmetallic substances as well as high temperature ceramics, as, for example in the melting of free floating refractory materials subject to contamination when in contact with any crucible or mold. Production of pure materials, materials with components added in precisely specified locations, and very large crystals free from imperfections, appears feasible. In earth orbit, semiconductor materials and ceramics could conceivably be refined in sizes limited only by the stability of the liquid melt under surface tension. Achievements in these areas are of considerable scientific interest, and have the promise of practical applications.

Such processes as materials purification, homogenization of alloys having large density differences between phases, preparation of new alloys, semiconductors, and mixed crystals and glasses are also feasible. Ultra high purity glasses, growth of crystals directly from the levitated mass, and solidification involving extreme supercooling are other possibilities. One characteristic of supercooled material is the formation of extremely small crystal grains, which appears to be the mechanism by which materials achieve superplasticity. Elongations in metals of greater than 1000% have been observed (12). Another interesting area to explore is the solidification of normally crystalline materials as amorphous glasses when they are supercooled without contacting container walls. Drop tower experiments at Sandia Laboratories, for example, have produced 2- to 3-millimeter droplets of enstatite (magnesium silicate) which are totally transparent and totally amorphous. (13,14) Totally new glasses produced in this manner are likely to have interesting properties, such as high index of refraction or low dispersion.

Floating-zone melting is another process with great potential. Relaxation of present restrictions on the size of the molten zone should permit application of this technique to materials which are not now feasible on earth. In addition, crystals of much larger diameter could be grown (15).

Convection currents have been shown to be a source of dislocations and other inhomogeneities in crystals grown from the melt (16). Suppression of these currents should reduce the number of imperfections. In fact, it may be possible to grow very large dislocation free crystals from nonmetallic substances. For crystals grown from solution or vapor, the absence of convection would cause the process to become diffusion controlled. As a result the growth rate could be reduced, possibly allowing greater precision in control of additive components.

The weightless condition could eliminate the need for supports, another major source of imperfections (10,17). Seed crystals could be suspended in contact with the melt, solution, or vapor. The absence of stresses in crystals grown by pulling could allow much larger perfect crystals to be grown by this technique.

Single crystals of high perfection are in great demand for many applications. The technology of crystal growing is an extensive and rapidly growing field, and perdictions of the future value of any particular technique are difficult to make. Nevertheless, the weightless environment of space does offer some possible solutions to currently unsolved problems.

B. Novel Structural Materials

Whole new classes of alloys, colloids, and variable density solids and solid/gas mixtures utilizing characteristics of the zero-g environment can readily be conceived. These include high strength foams, metallic and nonmetallic mixes, variable density melts for casting, etc. Other than their utilization as subject materials in basic research, however, it is difficult at this time to assess the benefits derivable from such materials. For example, it may be possible to fabricate high strength foams and structures by controlled distribution of gas bubbles, but it is not clear that such materials offer advantages warranting space processing. The problem is not visualizing new materials, but establishing justification of their worth. There may be possible uses of such materials <u>in</u> space but at present these do not look as promising as competitive approaches utilizing assembly of modularized structures.

Particularly promising applications of new structural materials are the high strength composites, considered in some detail to illustrate possible benefits derived from zero-g processing.

High strength to weight composite materials are formed by embedding microscopically thin, dislocation-free crystalline whiskers in a matrix or filler material. In practice, bond failure between the whiskers and filler is the governing failure mechanism. Composite material strength can be increased by 1) using longer elements and, 2) achieving optimum whisker spacing and alignment. In the earth environment, practical problems associated with physical spacing and alighment of whiskers in the matrix material are prohibitive and are responsible in large measure for current high costs of composites which sometimes are thousands of dollars per pound. In zero-g, it may be practical to grow longer whiskers from free-floating droplets and also to alleviate spacing and alignment problems. For example, polarization techniques could be employed to stratify and align crystals along desired axes. Matrix material could be vapor deposited to achieve uniform "wetting" at the bonding interface and maintain uniform spacing and alignment.

C. Forming Processes

In the absence of a gravitational field, forces of secondary influence in the earth environment become of paramount importance. For example, materials in the liquid state rapidly take the form of perfect spheres under the influence of surface tension. Likewise, spun liquid masses form accurate ellipsoidal shapes.

Numerous forming processes which depend on the lack of convection and the absence of gravity separation and distortion have been proposed (4,5,10,11). These include thin wall membranes and castings, forging and extrusion of long, delicate structural components, blow molding of complex components, and a variety of casting techniques utilizing materials of differing densities.

A case in point, demonstrating the need for further understanding of these processes, is a suggested method of fabricating hollow ball bearings (5). These are very desirable and are under active investigation at the present time, with imperfect results to date. In space, formation of a hollow sphere by injecting gas into the center of a molten ball would appear to be a straightforward technique. Further investigation, however, reveals several significant problems (18).

- The gas bubble may not stabilize at the center of the sphere.
- The change in density upon solidification may lead to a final form that is non-spherical and highly stressed.
- The crystalline material may form surface facets and internal branch-like formations (dendrites) due to differential solidification rates of alloy components.

Some of these, notably the surface facets and dendritic growth, are of considerable interest in crystallography.

These potential problems might be avoided in various ways. For example, if rapid, homogeneous nucleation of fine crystals in the melt is achievable by supercooling, a smooth surface may result. The point is that even the simplest appearing processes would require an extensive development program in zero-g before a practical product could be made.

IV. SUMMARY AND CONCLUSIONS

A. Summary

Areas have been identified where useful and unique products and processes may be developed in the zero-g environment. In particular, material refining and crystal growth appear to offer attractive possibilities for creation of new materials whose properties would be of great scientific interest and economic worth.

Many new structural materials with highly desirable characteristics, and unique forming processes can be readily conceived. The problem here is not one of visualization but, rather, the lack of information required to evaluate their worth relative to earth produced competitors.

B. Conclusions

1. Too little is known about the actual behavior of processes in zero gravity to clearly justify a substantial commitment to developmental research in this area. Experiments must first be carried out to identify areas in which unique and worthwhile results can be obtained.
2. Science should be emphasized in the early stages so that basic materials phenomena are more fully understood. Useful applications will come as a natural outgrowth of discovery.
3. We believe that good experiments can and should be planned in limited areas such as crystal growing and levitation melting, which do appear to offer obvious potential. Early experiments could be undertaken utilizing materials whose behavior is well understood to provide a point of departure for further investigation.

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1013-MHS
1011-LDS-rghe
1015-ARV

Attachments
  Appendix
  Bibliography

A-1

APPENDIX

LIMITATIONS ON ZERO-G

Earthbound simulations of zero-g are limited to periods of a few seconds in a drop tower or about one minute in an airplane. Rockets can provide weightless intervals of several minutes, although these are necessarily preceded by periods of very high acceleration. Only in space can longer periods be achieved.

In an orbiting spacecraft, free-floating objects travel in independent trajectories and some restraining force will be required to avoid hitting the walls of the container. For example, without the restraining force, an object travelling in the orbital plane and placed one foot above and one foot in front of the center of gravity of the space station would describe the trajectory shown in Figure 1 (19) where X and Z refer to tangential and radial axes fixed in the space station. The average distance which such an object drifts along the X axis during one orbit is equal to $-12\pi Z_o$, where Z_o is the vertical distance from the center of gravity. The minus sign shows that, for positions above the X axis, the object is drifting backwards while for positions below X axis, the object moves forward. Note that the average drift distance per orbit is independent of the orbital altitude.

The acceleration required to alter an object's trajectory to maintain its position is very small (on the order of 10^{-7}g) and it is expected that the maximum accelerations will be those due to astronaut body motions if thrusting is inhibited during these periods. Assuming that position control accelerations of 10^{-3} - 10^{-4}g could be allowed during melting and casting operations, the position of a levitated mass relative to the spacecraft could be maintained despite the influence of astronaut body motions. (10)

The influence of acceleration due to positioning forces results in a shape distortion of the molten mass. For 10kg of molten metal with a surface tension of 1000 dyne/cm and density of 8gm/cc, the acceleration which causes its surface curvature to differ by a factor of two across the diameter is approximately 10^{-3}g. Rotation also causes distortion and, for the above 10kg sample, a rotational period of a few seconds results in an oblate spheroid having a curvature at the equator twice that at the poles.

Lorentz forces will distort the floating fluid if eddy current forces are used for position control or if RF fields are used for heating or stirring the specimen. The main limitations in RF levitation work will be removed, by zero-g, but others will eventually be encountered due to potential failure of the integrity of a molten mass if the processing of too large a batch is attempted.

The main disturbing forces will arise from the requirement for position control within the facility. Application of RF position restoring forces will initiate shape oscillations in a molten mass. Since molten metals possess viscosity, such oscillations will diminish with time. The damping time is proportional to the square of the radius of the sphere and inversely proportional to the kinematic viscosity. For a 10cm radius spherical mass of density 10gm/cc and viscosity 2-4 centipoise, the time constant for damping will lie in the range of thousands of seconds. For spheres with radii near one cm, the damping times will be tens of seconds.

TYPICAL TRAJECTORY OF FREE FLOATING OBJECT
(VERTICAL PLANE)

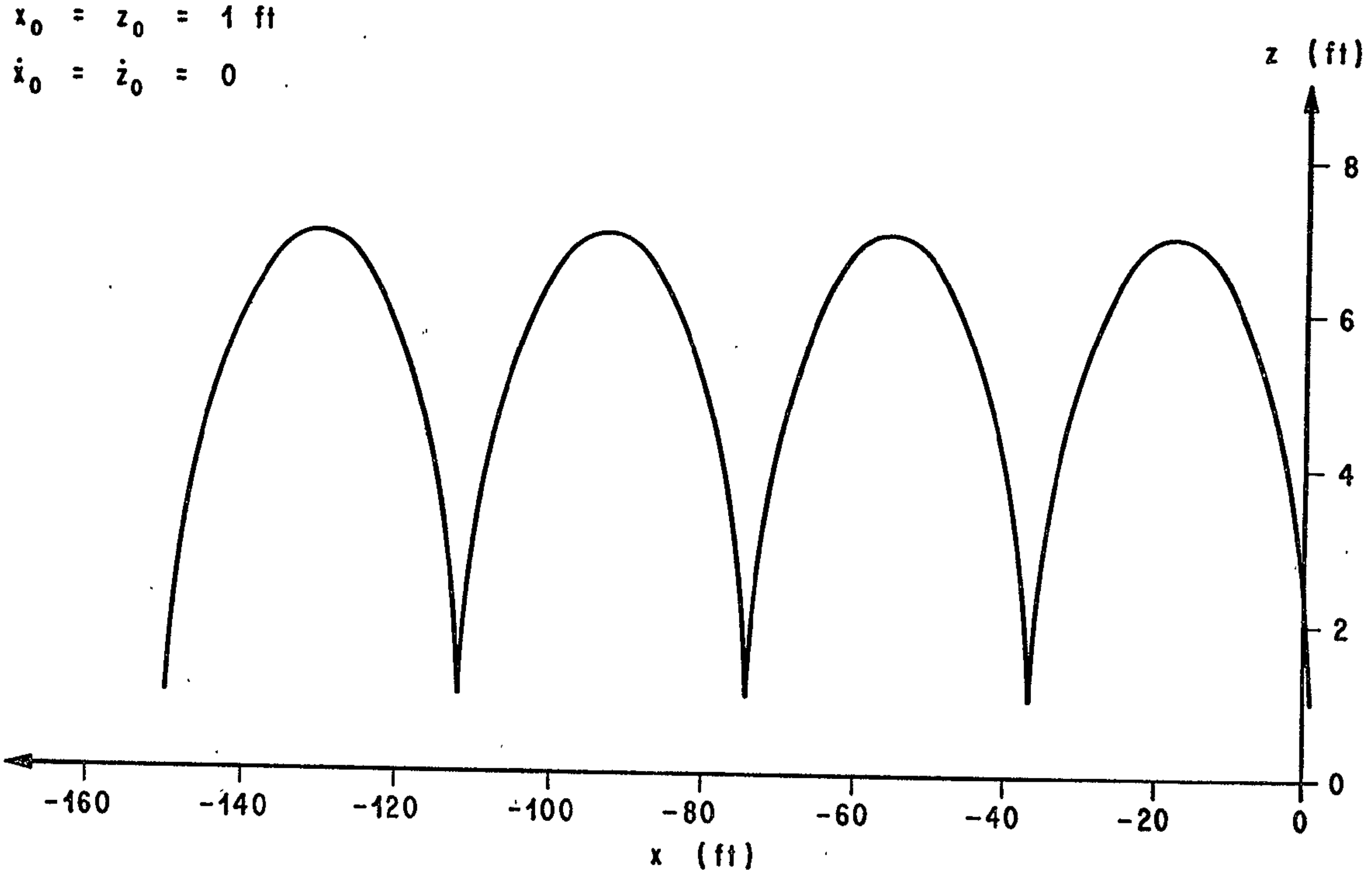

FIGURE 1

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