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# UNIQUE MANUFACTURING PROCESSES IN SPACE ENVIRONMENT



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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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# UNIQUE MANUFACTURING PROCESSES IN SPACE ENVIRONMENT

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## ABSTRACT

The zero gravity or weightless environment during orbital flight makes specific new manufacturing processes possible.

An overview of the current research and technology projects is given. Unique processes are discussed and potential materials and products groups are outlined.

The Space Manufacturing experiments presently in development for the Skylab Orbital Workshop mission are briefly described and follow-on NASA plans and the industrial participation in space processing and manufacturing experiments are outlined.

## INTRODUCTION

While the exploration phase of our space capabilities in earth orbital flight is still under continuous development, the exploitation is already successfully underway in unique world-wide communications and weather observation applications.

The utilization of the unique environment of space flight for producing things which cannot be made on earth has entered the exploratory development phase. The purpose of this presentation is to show the obviously existing feasibilities for orbital manufacturing and furthermore to discuss the current projects and outline briefly the future plans.

## FUNDAMENTALS FOR MANUFACTURING IN SPACE

Space environment offers unique vacuum, temperature, pressure, radiation and gravity characteristics. With the exception of the orbital gravity characteristics, all other space environmental factors can be simulated on earth and are widely used in existing terrestrial processes.

Gravity of one-g is the natural environment for all terrestrial processes. In addition by superimposed accelerations, higher g load levels can easily be produced and are common processing means as, for instance, in centrifugal separation. It is different with processing in a lower than one-g environment or weightlessness, because this condition can only be produced during free fall motions and is restricted to durations from fractions of seconds to about 30 seconds during the free fall trajectory flight in an airplane. On earth only very few but remarkable manufacturing processes of very short processing cycle are able to use the lower than g level. An example is the free fall casting of lead shot, which was utilized centuries ago by pouring liquid lead through a screen atop the shot towers. Another example is the "atomizing" of metals and nonmetals to powders, tiny glass spheres and even hollow spheres called "microballoons". However there is no process possible where a true equilibrium condition is reached until the free fall duration is extended to great length. This happens only in orbit where the satellite or complete manufacturing facility is consistently free falling around the earth.

Looking at the low and zero-g environment, we can compare our situation now to what happened during the 17th Century with the discovery and development of vacuum processes. Until then every process was at or above one atmosphere air pressure. The development of vacuum processes was actually delayed because of the Horror Vacui philosophy. Once this philosophy was overcome, such technological developments as the steam engine and the vacuum tube were made possible.

The discovery of the vacuum or rather of the fact that we can escape our "Ocean of Air" belongs to the history changing events. With the development of rockets which enable us to get into a steady environment of lower than one-g, we can extend and improve on free fall processes which on earth cannot last longer than a few seconds. With our capability to go into orbit, where we can escape from our highest order environment, the "Ocean of Gravity", we can readily see that any process affected by gravity could be drastically changed in space. I think one can rightfully express the gravity environment similar to the recognition of other major environments as an ocean, like the "Ocean of Air" and the "Ocean of Water". Figure 1 shows how the action of gravity can be compensated by a hydrostatic pressure field, a hydrodynamic pressure field or by a centrifugal force field in orbital flight. The close resemblance between the neutral buoyancy condition in water and the "free suspension" or weightlessness in space is the reason for the widely used simulation of space operations underwater. The static, apparently motionlessly floating in water which we all know can be compared to a floating in the "Ocean of Gravity" during space flight.

Processes sensitive to buoyancy and thermal convection would without doubt be basically changed in the absence of gravity and molecular forces come into play and would become major processing factors. Figure 2 shows how different sand in water behaves. Figure 3 shows that a candle does not sustain burning, and Figure 4 demonstrates that the gravity field changes any thermal imbalance into a velocity field as is best seen in the formation of a cloud. Such very often violent mixing actions are ever-present at any phase change, like during the solidification of materials on earth, but this will be very different in space.

Before we can fully exploit the possibilities for processing in a reduced gravity environment, we must understand the implications. For instance, in our one-g environment we melt metals and the low density material comes to the top. This is an advantage in purifying the metals. On the other hand, solidification and crystallization are irregular because of buoyancy and thermal disturbances so that the cast material is not good enough for many applications. We build factories to refine these irregular crystals by hot rolling, cold rolling, forging, etc., and then we machine the material to get it into the shape and size wanted. This of course requires a large investment and in fact is the major investment in industry, which can also be interpreted as a penalty for living in our "Ocean of Gravity". Now, if we can mix something into the liquid metal and we can use the zero gravity effect of no buoyancy and no thermal convection, it may be possible to obtain full properties in a cast metal. These are consequences which sound simple but could be far reaching.

In looking at some well-known facts found in physics books, we can see the possibilities of processing in zero-g. Figure 5 shows that the viscosity of water and liquid metals is of the same order of magnitude. Liquid lead is only twice as viscous as water, whereas a drop of engine oil is two thousand times as viscous as water. This chart shows that the surface tension of iron increases by a factor of 20 over that of water. We can also get an idea how fast liquid materials contract in zero gravity to form perfect spheres. A drop of water contracts from an irregular shape to a perfect sphere with a surface velocity of about 150 miles per hour. In the case of liquid iron, the velocity is nearly that of sound. This means that the molecular forces of surface tension versus viscosity are so powerful that materials will assume the equilibrium shape of a sphere almost instantly. Of course this is valid only for small droplets where mass forces can be neglected. The message of this chart is clear that molecular forces become significant in the zero gravity environment of space. Since molecular forces can be used as a means of processing material, we would expect that tolerances will be improved by several orders of magnitude. To machine something within ten thousandths or maybe 25 millionths of an inch is quite expensive. Because we are talking about molecular forces and sizes, we may be able to produce spheres in zero-g that are accurate within angstrom units.

Figure 6 shows the relations in a soap bubble or pressure vessel between the pressure which can be contained, the hoop stress $\sigma \sim t$ and the diameter D. The smaller the diameter, the higher the pressure capability if the wall thickness is kept constant. In the case of a very small pressure vessel like a droplet of water $10^{-6}$ centimeters in diameter, the hoop stress is produced by the surface tension $\gamma$ of water. This is very small but still in such dimensions produces a large internal pressure of 5,000 psi. This is another indication of the powerful nature of the forces available for processing. In a droplet of iron the increase in surface tension by a factor of 20 would yield a reaction pressure of 100,000 psi. Looking at the possibilities from an engineering viewpoint, we try to determine how these phenomena can be used in manufacturing. In addition to these molecular forces, we have other possibilities which may be helpful. One is in the solidification of metals. Solidification mechanics is a big and complicated science. Some basic concepts that may be possible in zero gravity are:

1. Controlled radiation cooling without thermal eddies.
2. Supercooling of liquid phase.
3. Nucleation control through solid, powder and fiber dispersion.

First of all we can cool materials without the disturbing convection currents and we can eliminate contamination by keeping the materials in a free floating condition. Secondly, we may be able to supercool a liquid metal because there is no disturbance. Third, we may be able to control nucleation by the dispersion of powders and fibers within the liquid metal. We have shown that liquid metals are as thin as water, and to be able to mix particles in a liquid metal on earth is as hopeless as mixing sand in water under one-g conditions, but mixture stability can be achieved under zero-g condition.

Figure 7 shows the two main categories of unique zero gravity processes. Examples are illustrated in Figures 8, 9, 10, 11, and 12. A more detailed description can be found in References 1, 2, and 3.

In summary, the major importance of the weightless environment lies in the fact that materials in liquid state become objects in their own right. From our terrestrial experience, liquids alone practically do not exist. They always need a container. The ever-present action of gravity causes buoyancy, separation and thermal convection during the interaction with other liquids, solids and gases, and is overshadowing and preventing many processes. Furthermore, on macroscopic scale, molecular forces such as cohesion and adhesion do not play a large role, while in zero gravity they represent process controlling factors, even in the largest bulk processes. Our terrestrial idea of the possible and practical size of processing equipment and facilities might need adjustment--because the disappearance of the dead weight will allow us to build things of truly extra-terrestrial dimensions. The potential processes and products we are discussing now are only a very bashful beginning of exploiting our new access to zero gravity. If one would have asked Toricelli (the inventor of the vacuum pump in 1650) what his vacuum was good for, and if he would have answered that this opens the age of power engines and television, nobody would have understood. We are presently in a similar situation with respect to our new access to extra-terrestrial production environment.

## RESEARCH AND DEVELOPMENT IN SUPPORT OF SPACE MANUFACTURING PROCESSES

Space processes presently under investigation are tabulated in Figure 13. Under A. processes are listed which use the buoyancy and thermal convection free environment, and under B. processes which are controlled by the inherent cohesion and adhesion forces during the liquid phase manipulation. This chart also shows the Materials Groups presently involved and also the potential Product Groups which might emerge during follow-on space manufacturing activities.

The list of processes which promise unique results in space environment is steadily growing. The enclosed list, "Classification of Space Processes", in the Appendix accounts for the presently identified areas.

A large number of conceptual studies and evaluation of economical aspects have been considered and are in progress in industry, at universities and research institutes, and government agencies. Studies in industry which might lead to future Space Experiments are listed in Figure 14, and NASA funded studies on Space Processes are shown in Figure 15. Detail discussion of all these subjects can be found in the Proceedings of the Space Manufacturing Meetings at MSFC (References 1 and 3).

Presentations in this special Session provide a cross section through the most essential activities. Dr. Frost has established the theoretical basis and proven by laboratory demonstration the free positioning of masses in low gravity environment for containerless melting. Dr. Steurer has established the theoretical background for the feasibility of a large number of unique Space Processes and is developing unique composite casting applications. Dr. Kober has pioneered the space manufacturing area in the chemical and biochemical field. Mr. Berge has participated in the MSFC development of mechanical positioning and handling devices in weightless environment. (References 5-8)

Let me give a typical example of the problems which arise during the development in this area of weightless environment, which is completely abstract to our experience. One unique application was postulated to be the making of precise hollow spheres. It soon became obvious that the concentricity of the original gas pocket in the sphere is not self-adjusting because gas bubbles in a liquid in weightless environment stay where they are. It was found that application of acceleration will equalize the wall of the sphere. Acceleration of the wall mass generates a hydraulic pressure which causes the thicker portion to run into the thinner portion of the wall until the sphere has a uniform wall thickness. Radial acceleration can be caused by pulsing the environmental pressure which causes expansion and contraction of the sphere. Also, angular or translatory accelerations over two axis or planes will cause symmetric wall distribution. The spinning or translation can be induced during the electromagnetic crucibleless suspension of the material.

The degassing of liquefied materials in freely suspended position provides another interesting problem. Figure 16 is self-explanatory how gas separation can be accomplished within a crucibleless melting process. Dr. Bauer has examined theoretically the gas-liquid interaction in zero gravity (Reference 4). He found that even a liquid sphere without any gas bubble assumes a toroidal configuration as a consequence of free spinning. The unitized surface shapes for a quarter sphere at different angular velocities are shown in Figure 17. The stability limitations for achieving such shapes were not yet theoretically established but are intended in a follow-on phase to this work.

Let me mention finally that extremely high vacuum can be made accessible even at low orbit by positioning of processes into the rarefied flow field in the wake of a shield. Figure 18 shows an early projection of the pressures available. Air-free chemical preparations and refinement processes might be greatly enhanced by this new approach.

## SPACE MANUFACTURING FACILITY AND EXPERIMENTS FOR "SKYLAB" ORBITAL WORKSHOP I

The "Skylab" Orbital Workshop, Figure 19, is scheduled for flight in 1972. A first version of an experimental Space Manufacturing Facility, Figure 20, is presently in the hardware phase of development and will be installed into the "Multiple Docking Adapter" which is the unit closest to the center of Figure 19. In orbit, the interior of the manufacturing chamber will be vented through the outer wall of the workshop to provide vacuum environment as required for some process investigations. For welding, melting and heating, there are three power sources available. The main system consists of a battery powered electron beam gun of 2 KW power at 20 KV for 10 minutes continuous operation; furthermore, exothermic heating devices are used for brazing and sample melting and finally 150 W on-board power is available for sustaining slow cooling rates.

The Experiment carries the number M512 and consists of six experiment groups which will be conducted in this facility:

1. Welding Experiments.
2. Exothermic Brazing Experiments.
3. Single Crystal Growth Experiments.
4. Composite Materials Melting Experiments.
5. Sample Melting Experiments.
6. Flammability Experiments.

Detail descriptions of these experiments can be found in Reference 3.

There will be another experiment M507 on-board concerning handling of hardware in space. The "Gravity Substitute Workbench" works with electrostatic attractive forces for positioning of parts. Another version uses aerodynamic forces produced by an air flow through a screen covered table, Figure 21.

## SPACE FLIGHT PLANS

The "Skylab" Orbital Workshop I mission scheduled for flight in 1972 is filled up and the experiments M512 and M507, which are approved for this mission, are presently in the final hardware development phase. This present activity is quite limited, however, and the facility available in which to carry out these experiments is modest.

These flight experiments and supporting studies should provide a base from which to progress into a more ambitious effort on the second Workshop. Current planning considers following the first Workshop with a second one launched in early 1974. This Workshop would be the same basic configuration as the first but with new and improved payloads. Planning calls for at least four manned logistic missions spaced at 90-day intervals to support the program. The second Workshop is planned to be continuously manned with a crew complement of three and will be designed for an operating life of 12-18 months. It would operate at an altitude between 210 and 270 miles at an inclination up to 55°. Payloads for this program will emphasize the experimental facility approach with the idea that NASA will provide basic research laboratories available to participating scientists and engineers to carry out investigations of interest and value to the various disciplines.

It is unlikely, however, that we will have reached a point where commercial application is a reality. Rather, we think it will be necessary to continue our exploratory effort through more ground-based studies of promising processes and development of flight experiments to verify concepts. This is how we have structured our program approach as shown in Figure 22. We would expect to handle more complex processes than on the first Workshop and allow verification of certain techniques proposed by industrial organizations which may have commercial application. The flight facility envisioned for this phase would be improved and more versatile than our initial chamber. It probably will consist of several elements for positioning, heating and processing materials, for growing crystals, and for blending of composites. Hopefully, it will be capable of accommodating experiments developed late in the program and carried up to the Workshop on resupply missions.

By the mid-70 time period when the Space Station becomes available, we should have progressed so that we can identify processes that are commercially attractive. A major share of the responsibility for determining and developing these experiments and processing equipment should be assumed by industry.

NASA plans to provide a capability for carrying out investigations of industrial processes both within the confines of the basic station and later in a detachable module. It is doubtful if either the funding or the technology will be available to provide an independent module for operation at the beginning of the Space Station program. Rather, it is expected that a more advanced facility, evolving from our previous chambers, will still be of value and provide the necessary continuity to bridge the gap between the second Workshop and a separate module. Thus, in our program approach we have included a third generation space processing laboratory, integral to the Station for continuing materials processing studies. Since the Space Station will be functional for five to ten years, this laboratory should maintain its utility for an extended period of time. It need not become outmoded when the Space Manufacturing module becomes available and should be designed with sufficient flexibility to allow updating and expansion in orbit. Space processing equipment could then be developed and delivered well downstream of program initiation for use with this expanded facility (shown by the hatched bars on Figure 22).

By the late 70's we should have acquired sufficient experience to justify deployment of an independent module for space manufacturing. It would be capable of supporting commercial production of economically feasible products growing out of earlier investigations. It could be operated either attached to the mother ship or separate in a free flying mode when environmental conditions for certain processes dictate. This module might be thought of as our initial plant or factory in space, utilized by industry for profitable operation. Initially it would be government-owned and operated, leasing space to industrial organizations for their special needs. Ultimately it, or facilities like it, could be privately owned and operated much as COMSAT is today.

## PROGRAM DEVELOPMENT FOR SPACE MANUFACTURING

The present NASA Space Flight Plans, as shown in the previous chapter and in more detail in Reference 3, call for a realistic and aggressive development of Orbital Processing Facilities, which will lead to commercial utilization of Space Manufacturing in the late 70's.

It is important to remember that the challenge of Space Manufacturing lies in the exploitation of the extra-terrestrial environment and only processes which do not work satisfactorily or not at all on earth will justify such a big investment. There is a difference in degree of difficulty. Space Systems of present state-of-the-art are developed on the basis of terrestrial processes. Their functions are developed, optimized and verified on earth and the requirement is only that the system will repeat this same function in space. The engineering task up to now was to make terrestrial systems compatible with the space environment.

The new challenge is to start with an abstract system which functions only during the extra-terrestrial environment of weightlessness. The engineering task is to develop such a system in our terrestrial environment.

A fairly large number of unique processing ideas have been accumulated during the past two years. The chart, Figure 14, shows a concentrate of ten typical experiments from about 50 ideas, which have been proposed and studied to more or less depth. The major problem for the single experimenter is the involved and complicated interface with the different partners of the total space mission, like Launch Operations, Orbital Operations, Communication, Recovery and others. On the other hand, the participation of a large number of researchers during the exploratory phase of the coming years is of vital importance for a successful program development, because the "homework" for many processes is restricted to theoretical work and drop-tower verifications of the "trend" of the new process, while the only valid answer can come from orbital flight operations. We must therefore find a practical and cost effective mode of operation. The means of achieving this goal are seen in the subdivision of the total interface by the development of a number of specific facilities consisting of subsystems suitable for groups of related experiments.

The up-to-date proposed unique processing ideas show a large commonality in experiment facility requirements which can be provided in three basic space processing facilities:

I. Orbital Facility for Space Melting and Casting.

II. Orbital Facility for Space Crystallization and Solidification.

III. Orbital Facility for Space Fermentation and Separation.

With the advent of new types of experiments, rather a new Orbital Facility should be defined with subsystems fitting the new groups, instead of modifying earlier facilities to an extent reflecting back into the interface with the single experimenter. It is hoped that a steady frame for the activation of a larger number of exploratory experiments will be established this way. The provision by NASA of a well-defined general capability for carrying out investigations of industrial processes within the confines of the Workshop Facilities and later on larger scale in the Space Station will keep the cost of the experiment itself to a minimum. That way many laboratory developments of new processes and materials will have access to the steady state zero-g environmental testing.

The following major subsystems are presently planned for the Orbital Facilities:

I. Orbital Facility for Space Melting and Casting

1. Radiation Furnace System.
2. Free Suspension and Induction Melting System.
3. Composite Casting and Foaming System.

II. Orbital Facility for Crystallization and Solidification

1. High Density Crystal Growing System.
2. Directional Solidification System.

III. Orbital Facility for Space Fermentation and Separation

1. Fermentation System.
2. Electrophoresis Separation System.

Phase A development effort has been accomplished for the subsystems of Facility I. Continuation is planned for the coming fiscal year. As soon as the final definition for the system and the interface with the experiment using the system is established, it is presently considered to issue an "Announcement of Flight Opportunity" by the responsible NASA Program Office as an open invitation to any qualified participant wishing to submit proposals for experiments to be processed in the government-furnished Orbital Facilities.

The Orbital Facility development plan seems presently the best means serving groups of related experiments. New important ideas for space manufacturing experiments requiring specific facilities are not in any way restricted and will lead to expansion of our plans. We shall probably not only have two Orbital Workshops but more, so if an experiment cannot be accommodated for lack of lead time for the second Workshop, it will very definitely be considered in a revisit or follow-on mission. The climate for realizing and applying our capability in space was never better. We are looking forward to your participation.

## APPENDIX

### CLASSIFICATION OF PROCESSES SENSITIVE TO SPACE ENVIRONMENT ESPECIALLY ZERO-g

1.0 Free and Captive Suspension
- 1.1 Crucible Support, Wetting/Nonwetting
- 1.2 Sting Support, Wetting/Nonwetting
- 1.3 Electromagnetic Field Support
- 1.4 Electrostatic Field Support

2.0 Mixing
- 2.1 Mechanical Mixing
- 2.2 Induction Mixing

3.0 Separation - Purification
- 3.1 Centrifugal Separation, Free/Container
- 3.2 Velocity Separation (Condensation/Selective Membrane)
- 3.3 Electrophoresis
- 3.4 Magnetic Separation (Mass Spectrometer)
- 3.5 High Vacuum Refinement; Centrifugal, Maragony Flow

4.0 Alloying + Supersaturation
- 4.1 Premixed Powders Melting
- 4.2 Thermo Setting or Diffusion Alloying

5.0 Heating
- 5.1 Resistance Heating
- 5.2 Induction Heating (HF)
- 5.3 Radiation Heating (IR)
- 5.4 Conduction Heating
- 5.5 Solar Mirror or Reflector Heating

6.0 Cooling
- 6.1 Radiation Cooling
- 6.2 Conduction Cooling (Passive/Active)
- 6.3 Space Shadow or Shield Cooling (Heat Sink/ Water)

7.0 Casting
- 7.1 Surface Tension Casting or Free Casting
- 7.2 Supersaturated Alloy Casting
- 7.3 Composite Casting/2-State/3-State
- 7.4 Adhesion or Layer Casting

8.0 Liquid State Forming
- 8.1 Blowing, Spherical/Die-Blowing
- 8.2 Electrostatic Field Forming
- 8.3 Adhesion Drawing or Surface Tension Drawing

9.0 Controlled Density Processing
- 9.1 Dispersion Foaming
- 9.2 Vaporization Foaming
- 9.3 Variable Density Casting

10.0 Deposition
- 10.1 Adhesion Coating
- 10.2 Galvanic Plating-Coating
- 10.3 Vapor Deposition

11.0 Solidification
- 11.1 Amorphous Solidification
- 11.2 Controlled Crystallization
- 11.3 Single Crystal Solidification
- 11.4 Directional Solidification
- 11.5 Supercooled Coining
- 11.6 Zone Refining

12.0 Melting
- 12.1 Complete Melting/Low/High Viscosity/ Overheated
- 12.2 Partial Melting; Matrix Melting in Cermets
- 12.3 Low Melting Intermetallic; Thermo Setting Alloys

13.0 Vaporization
- 13.1 Fractional Distillation
- 13.2 Pressure Drop Vaporization

14.0 Nuclear Processing
- 14.1 Fusion Breeding
- 14.2 Fission Breeding

15.0 Chemical Processing
- 15.1 Polymerization

16.0 Biological Processing
- 16.1 Fermentation
- 16.2 Separation
- 16.3 Distillation
- 16.4 Freeze Drying

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ILLUSTRATIONS

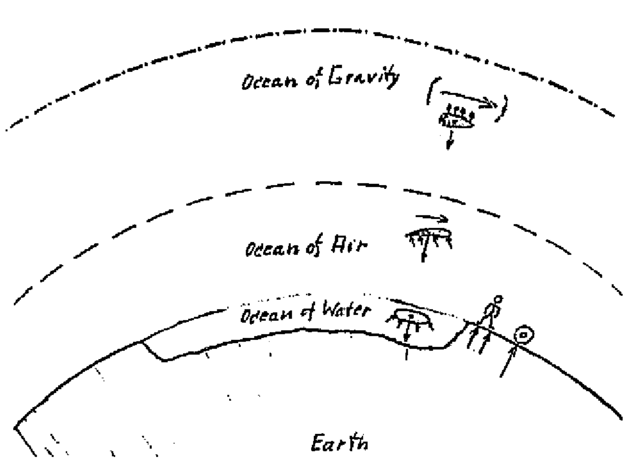



Figure 1. Oceans of Water, Air and Gravity

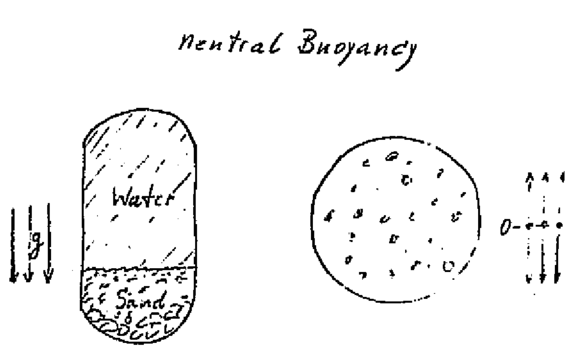



Figure 2. Sand in Water on Earth and in Space

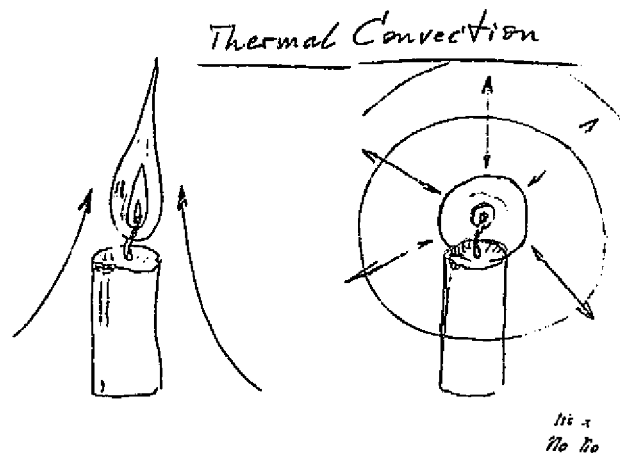



Figure 3. Candle Does Not Sustain Burning in Weightlessness

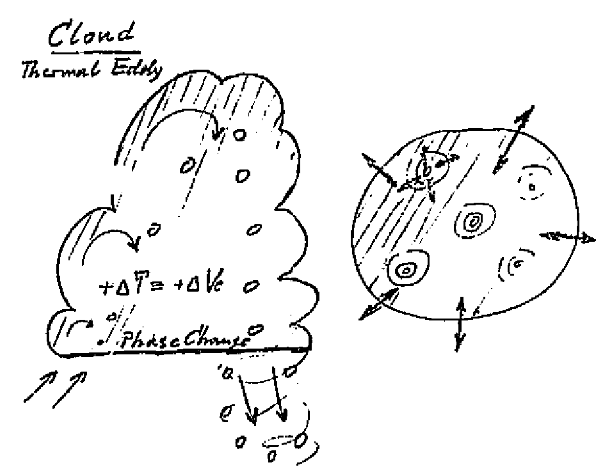



Figure 4. Cloud Formation Shows Gravity Changes Temperature Difference into Buoyancy Motion of High Velocity

MATERIALS DATA FOR THE LIQUID STATE

| MATERIAL | TEMPERATURE °C | SURFACE TENSION $\alpha$ DYN/CM | VISCOSITY IN POISE $\eta$ DYN SEC/CM$^2$ | DEFORM. RATE INDEX $\alpha/\eta$ CM/SEC | |
|---|---|---|---|---|---|
| WATER | 18 | 73 | 0.011 | $0.7 \times 10^4$ | 150 MPH |
| MERCURY | 20 | 465 | 0.021 | $2.2 \times 10^4$ | |
| TIN | 232 | 526 | 0.020 | $2.6 \times 10^4$ | |
| LEAD | 327 | 452 | 0.028 | $1.6 \times 10^4$ | |
| COPPER | 1131 | 1103 | 0.038 | $2.9 \times 10^4$ | |
| IRON | 1420 | 1500 | 0.040 | $3.7 \times 10^4$ | |
| ENGINE OIL | 20 | 15-30 | 10-20 | $1.5 \div 3.0$ | |
| GLYCERIN | 20 | (20) | 15 | 1.3 | |

DEFORMATION RATE V FOR A BODY OF THE SURFACE AREA A AND A DISTANCE BETWEEN SURFACES H.

$$\frac{dv}{dh} = \frac{F}{\eta A} = \frac{\alpha}{\eta}$$

Figure 5.

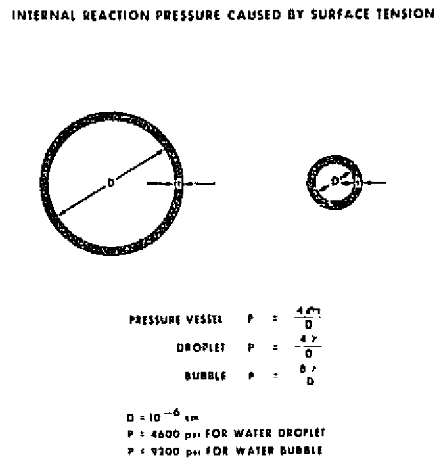



Figure 6.

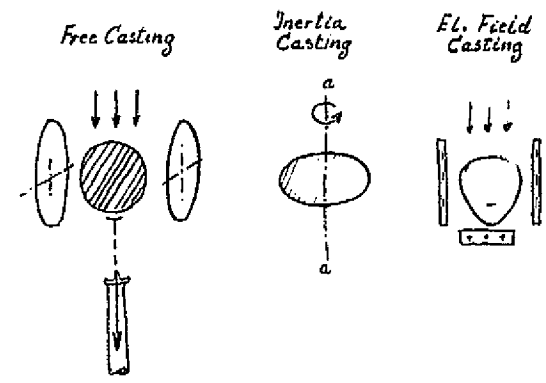



Figure 9. Casting Processes in Weightlessness

DEVELOPMENT OF UNIQUE SPACE MANUFACTURING PROCESSES

- LOW AND ZERO GRAVITY PROCESSES
  - A. BUOYANCY AND THERMAL CONVECTION SENSITIVE PROCESSES
    1. BLENDING OF MATERIALS OF DIFFERENT DENSITY IN PLASTIC MATRIX
    2. CONVERSION OF COMPACTED POWDERS AND COMPOUNDS INTO CASTINGS
    3. COMPOSITE CASTING
  - B. MOLECULAR FORCES CONTROLLED PROCESSES
    1. COHESION OR SURFACE TENSION CASTING
    2. ADHESION OR LAYER CASTING
    3. BLOW CASTING
    4. CONTROLLED DENSITY CASTING
  - C. COMBINED PROCESSES A AND B
- OTHER UNIQUE SPACE PROCESSES

Figure 7. Two Main Categories of Unique Zero Gravity Processes

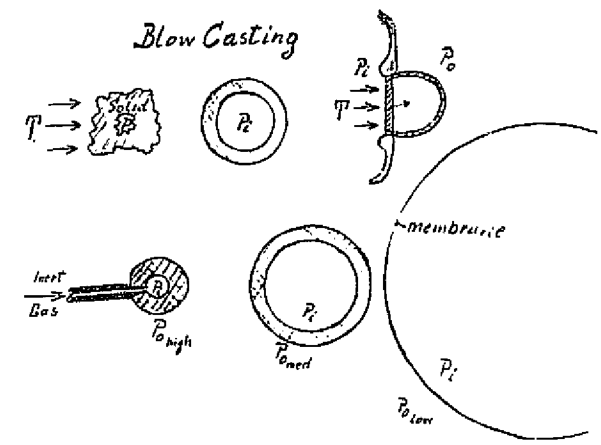



Figure 10. Blow Casting in Weightlessness

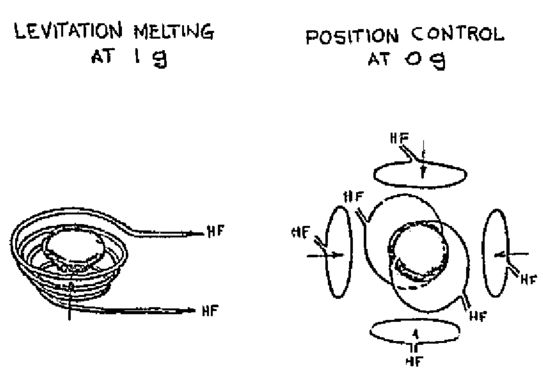



Figure 8. Levitation Melting and Position Control in Weightlessness

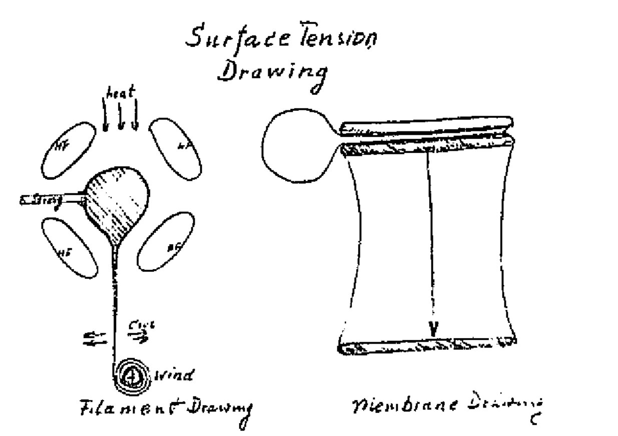



Figure 11. Surface Tension Drawing in Weightlessness

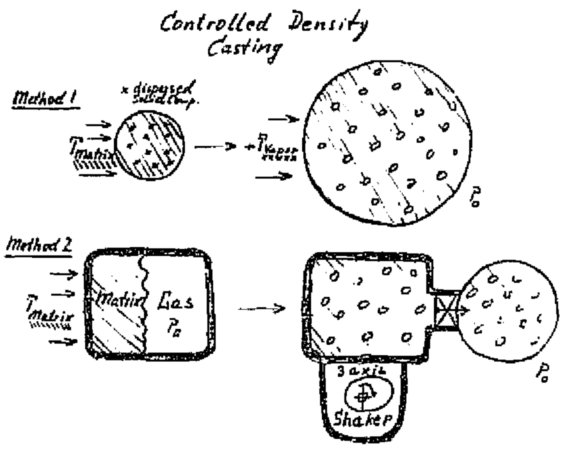



Figure 12. Controlled Density Casting in Weightlessness

| SAE-ME-DR 109 | SPACE MANUFACTURING UNIQUE TO WEIGHTLESS ENVIRONMENT | | SUMMARY |
|---|---|---|---|
| SPACE PROCESSES UNDER INVESTIGATION | | MATERIAL GROUPS | PRODUCT GROUPS |
| A. BUOYANCY AND THERMAL CONVECTION FREE PROCESSES: TOTAL 28 | | | |
| 1. FREE AND CAPTIVE SUSPENSION | 2 | | |
| 2. MOLDING | 1 | | |
| 3. SEPARATION & PURIFICATION | 5 | METALS | BALLS, SOLID AND HOLLOW, PRECISION PARTS |
| 4. ALLOYING & SUPERSATURATION | 3 | CERAMICS | HIGH STRENGTH-TEMPERATURE COMPONENTS, |
| 5. COMPOSITE CASTING | 2 | GLASSES | FILAMENTS, MEMBRANES, COMPOSITE |
| 6. SOLIDIFICATION | 6 | BORON | STRUCTURES, COATINGS |
| 7. DEPOSITION | 2 | ORGANICS | OPTICAL BLANKS AND COMPONENTS, ABRASIVES, |
| 8. NUCLEAR | 1 | COMPOUNDS | ISOTOPES, NUCLEAR FUELS |
| 9. CHEMICAL | 3 | CULTURES | ELECTRONIC COMPONENTS AND CRYSTALS, |
| 10. BIOLOGICAL | 3 | | SUPERCONDUCTORS |
| | | | VACCINES |
| B. COHESION AND ADHESION CONTROLLED PROCESSES: TOTAL 14 | | | |
| 1. SURFACE TENSION CASTING | 6 | | |
| 2. SURFACE TENSION DRAWING | 3 | | |
| 3. ADHESION CASTING | 1 | | |
| 4. BLOW CASTING | 1 | | |
| 5. CONTROLLED DENSITY CASTING | 3 | | |
| TOTAL A AND B: 42 | | | |

Figure 13.

POTENTIAL INDUSTRY EXPERIMENT STUDIES

Glass Manufacturing Experiment------------Dr. Deeg, American Optical Corporation

Metal-Ceramic Mixture Mfg. Experiment---- Dr. Mondolfo, Revere Copper and Brass

Boron Filament Manufacturing Experiment-- Mr. Witt, Grumman Aerospace Corp.

Polymerization Process Experiment--------- Mr. Foggarty, Grumman Aerospace Corp.

Composite Casting Experiment-------------- Dr. Steurer, General Dynamics/Convair

Thermo Setting Alloy Experiment----------- Dr. Steurer, General Dynamics/Convair

Vaccine Manufacturing Experiment--------- Mr. McCreight, Dr. Frost, General Electric/ Wyeth Laboratories

High Temperature Metal Oxide Experiment--- Dr. Frost, General Electric

Electronic Crystal Experiment (Delay Line)--- Dr. Henry, General Electric

Vaccine Production Experiment------------- Dr. Kober, Martin-Denver & pharmaceutical company(s)

Figure 14.

MSFC STUDIES ON SPACE PROCESSING OF MATERIALS

| STUDY | INVESTIGATOR | ORGANIZATION | PURPOSE |
|---|---|---|---|
| THEORETICAL STUDIES | | | |
| • [illegible] | [illegible] | UNIV. OF ALA. | • STUDY EFFECT OF GRAVITY ON CRYSTAL [illegible] GROWTH |
| • [illegible] | [illegible] | UNIV. OF ALA. | [illegible] |
| • [illegible] | [illegible] | GEORGIA TECH | [illegible] |
| • [illegible] | [illegible] | LOCKHEED | • EFFECTS OF SURFACE TENSION & CONVECTION ON CRYSTAL GROWTH |
| • [illegible] | [illegible] | [illegible] | • GROWTH CHARACTERISTICS OF MATERIALS IN ZERO "G" |
| STUDIES OF SPECIFIC PROCESSES | | | |
| • [illegible] | [illegible] | [illegible] | [illegible] |
| • [illegible] | [illegible] | [illegible] | [illegible] |
| • [illegible] | [illegible] | [illegible] | [illegible] |
| • [illegible] | [illegible] | [illegible] | [illegible] |
| SURVEY STUDIES | | | |
| • [illegible] | [illegible] | [illegible] | [illegible] |
| • [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] |
| FACILITY DEVELOPMENT | | | |
| • [illegible] | [illegible] | [illegible] | [illegible] |
| • [illegible] | [illegible] | [illegible] | [illegible] |
| SUPPORT OF AAP EXPERIMENTS | | | |
| • [illegible] | [illegible] | WESTINGHOUSE | [illegible] |
| • [illegible] | [illegible] | A. D. LITTLE | [illegible] |
| • [illegible] | [illegible] | [illegible] | [illegible] |

Figure 15.

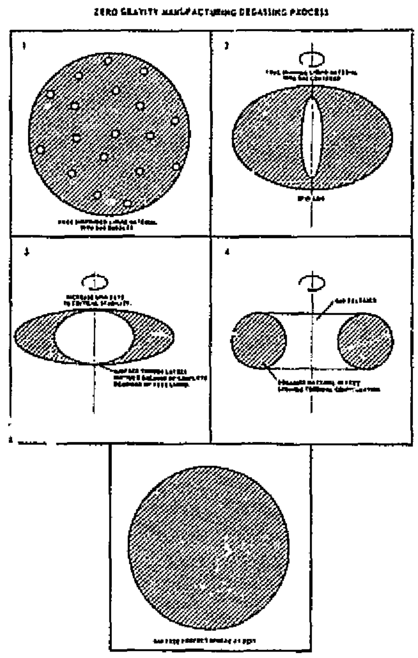


Figure 16. Zero Gravity Manufacturing Degassing Process

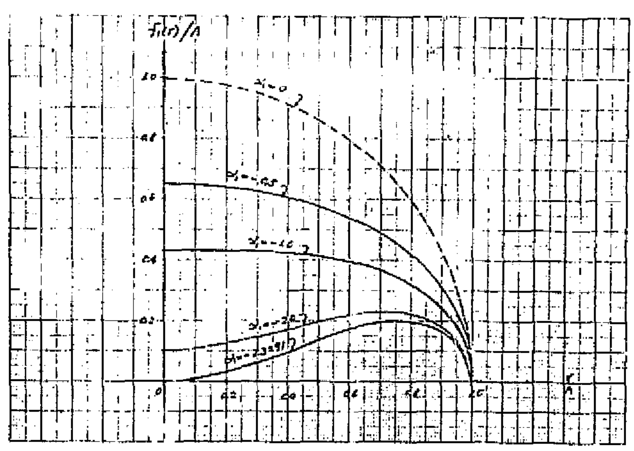
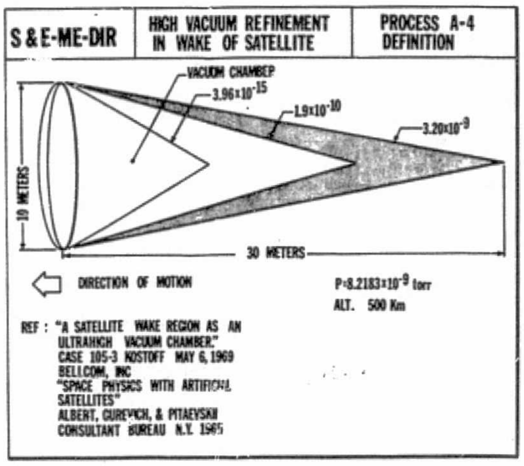


Figure 17. Unitized Surface Shapes for Rotating Liquid Material in Weightlessness




igure 18.

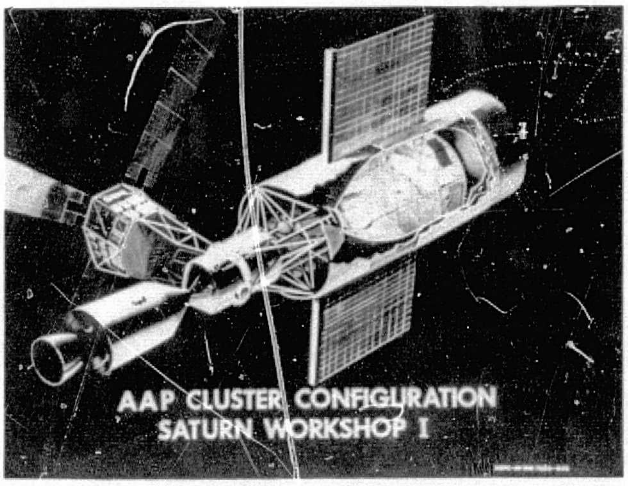



Figure 19. Skylab Orbital Workshop I

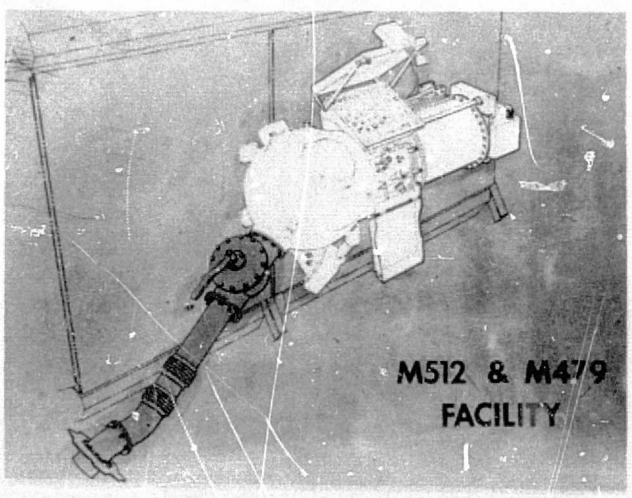



Figure 20. Space Manufacturing Facility for Skylab Workshop I

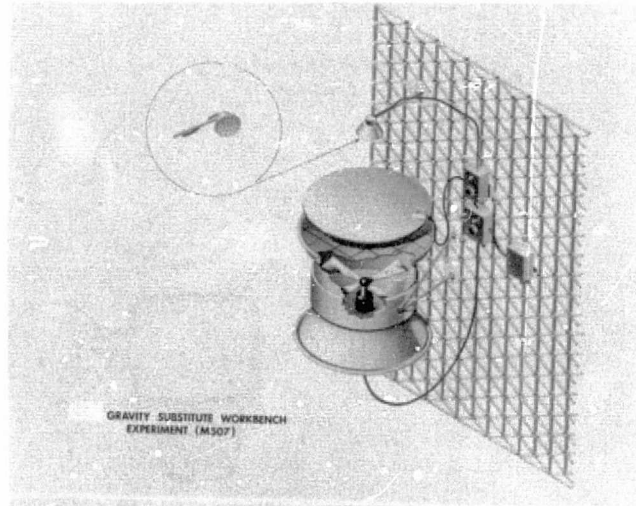



Figure 21. Gravity Substitute Workbench

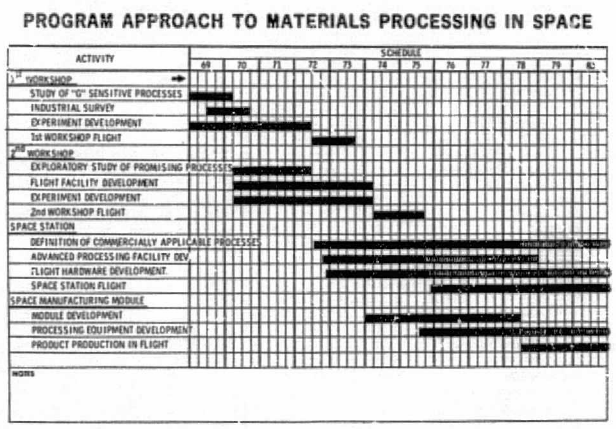



Figure 22.

N71-26011

# TECHNIQUES AND EXAMPLES FOR ZERO-g MELTING AND SOLIDIFICATION PROCESSES

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## ABSTRACT

Many new processes which can exploit the weightless environment of space have been suggested as possibilities for making improved or unique materials. A large number of these will involve, at some stage, a containerless melt or transfer of molten material. Some of the physics and technology problems associated with these processes are discussed. The range of applicability of some new electromagnetic process control methods is also presented.

## INTRODUCTION

The prospect of the availability of manned experimental facilities in the nearly weightless environment of near earth orbit opens up a number of exciting possibilities for basic studies in metallurgical and ceramic processing. Even at this point in time it appears likely that some of these experiments can lead to basic new insights into phenomena related to materials processing methods and, hopefully, to future commercial exploitation of new methods for production of selected products of high value. As space transportation costs are reduced with development of the space shuttle and reuseability concepts, the range of feasible materials processes will increase rapidly as products of lower dollar value per pound can be considered. It goes without saying that initial experiments should emphasize heavily the acquisition of new basic knowledge and that for some time in the future only commercial products having an extremely high monetary worth per unit weight can be considered for pilot production studies.

## EXAMPLES OF WEIGHTLESS MATERIALS PROCESSES

In two symposia which NASA has held at the Marshall Space Flight Center, a large number of specific suggestions have been made for new types of processes or for improvements in existing materials preparation methods which may be applicable in the future to commercial production of uniquely valuable products of relatively modest weight. I shall not attempt to summarize these ideas for exploitation of the removal of weight forces. Hans Wuenscher and other speakers in this session are covering many of these ideas. I will restrict my attention to new processes which make use of the following categories of phenomena attending the removal of weight forces:

1. The elimination of buoyant separation of melt phases of different densities.

2. The elimination of thermal convection currents.

3. The possibility for crucibleless melting of metals and ceramics.

4. The possibility for solidification in the absence of contact with molds.

5. Shape forming with surface tension and electromagnetic field forces.

We can think of many processes which exploit these new possibilities either singly or in combination.

### Elimination of Gravitational Phase Separation

Under the first category, namely the elimination of gravitational separation of melt phases of different densities, we can consider the following candidate products, which are a partial listing of ideas suggested to date:

1. Dispersions, emulsions and composite materials.

2. Alloys.

3. Foam metals.

4. Foam glasses.

Many dispersions of interest for metallurgical products involve components with widely different densities. Examples are rare earth oxide dispersions in superalloys, oxides of fissionable materials in metallic reactor fuel elements and dispersions of small particles of glass in a matrix having a different index of refraction to form phototropic materials or Christiansen filters.

Although it has been learned that cerium and lanthanum oxide dispersions in jet engine blade alloys containing chromium can greatly extend operational lifetime, these components presently require powder metallurgy techniques which result in relatively low creep resistance. Buoyant segregation of oxide particles presently prevents casting of these parts which could lead to improved properties and lower cost. The value of jet engine components is high enough that they are conceivable candidates for future space manufacturing if space transportation costs can be reduced to the extent that has been estimated by NASA for the 1980's.

Reactor fuel elements and control rods frequently use dispersion techniques to distribute particles of fuel or nuclear poisons in metallic elements. These particles are frequently in the form of oxides. Powder metallurgy techniques are often used. The dollar value per pound of parts within a nuclear reactor core is in many cases high enough to justify even large space transportation costs if casting of these parts can lead to significant increases in core lifetime.

In some alloys phase segregation can occur to an extent that buoyant segregation is encountered. For example, it is believed that buoyant separation of manganese from lead tin telluride thermoelectric material is observed before solidification and improved material was observed by rapid cooling of extruded needles. (1) It goes without saying for this example as well as all others in which consideration is given to a removal of buoyant separation in a weightless environment, that one must be assured that segreation cannot be as well prevented by other means. Rotating clinostats can be considered for prevention of segregation where the fluid circulation due to rotation is not detrimental. Another approach, of course, would be to continually stir the solidifying melt by the use of electromagnetic eddy currents. An alternate effect of weightlessness in such processes might also be restriction of grain growth by solidification at sub-cooled temperatures, discussed later below.

A number of alloys used in electric switching applications involve phases of widely different densities. The General Electric Switchgear Department currently utilizes such materials prepared by power metallurgy techniques. Casting of such components can conceivably lead to product improvements and again we speak of products of relatively high value in circuit breakers, relays, etc.

Elimination of gravity forces during fabrication of composite materials including dispersion particles or foams has been discussed by Steurer (2).

Although foam metals containing inclusions of gases are presently made by our Metallurgical Products Department, materials of much lower density and conceivably better structure could be made by foaming in a weightless environment. Such foams might have many applications (crushable structures, battery electrodes). Similar foams can be constructed from glasses. Formation of such foams and microspheres has been discussed by Steurer (2). Examples where the weightlessness of space would make possible significant improvement over products prepared in a gravity environment would be limited to parts of reasonably large size where normal solidification rates are low enough to allow separation and sagging in the presence of gravity.

When certain oxide electronic crystals are formed from glassy melts, gravitational settling of crystals to the bottom of the crucible is often observed due to the relatively high density of the crystals. Many of these crystals discussed by Henry (3) are of extremely high value and the potential for growth of larger crystals by avoidance of crucible contact is of potential interest.

Elimination of Thermal Convection

The effect of thermal convection in forming dislocations in crystals grown from melts has been described by Utech and Grodzka (4&5). Hamalainen (6) has also described frozen Bénard convection cells in thin alkali halide crystals. This work demonstrates the importance of thermal convection upon the crystal structure obtained. The effect of thermal convection during glass formation on the homogeneity of glasses has been discussed by Deeg (7). It seems likely that in many other cases the effects of thermal convection may have as yet unrecognized effects.

Crucibleness Melting

Limited studies of the potential for crucibleless melting of metals have been performed in terrestrial experiments where small spherules of metals have been levitated and melted by use of radio frequency induction fields (8 thru 22). The objectives of this work have generally fallen under one of the following categories:

1. Melting and reaction of refractory or reactive metals some of which are contaminated by any contact with crucible.

2. Formation of an alloy completely free from segregations.

3. Observation of subcooling below normal freezing point which can be achieved routinely with some metals.

The method has not found commercial application for several reasons. First, levitation is not practicable for poor conductors. Secondly, the required levitation power is often so high as to preclude separate control of specimen temperature. In other words, a reduction in RF heating of the specimen will cause loss of levitation or pouring from the bottom of the specimen. Instabilities are sometimes encountered, and in any event the mass of material which can be prepared is severely limited. Since levitation is the most obvious property of the weightless space environment, we can for the first time consider a whole range of new processes of this type and their potential application to preparation of large quantities of material.

Removal of the requirements for levitation of a crucibleless melt means that we can have complete latitude in heating of the specimen and its temperature control during solidification. Materials can be prepared which are nonconductors, and many suggestions have been made for new glass processes which should be possible in the space environment.

Besides the possibility for reacting and melting materials without crucible contact, a corollary is the ability to provide super heating to reactive and high melting metals for which skull melting techniques must currently be used. This opens up the possibility for precision casting of these materials which cannot at present be accomplished with the negligible superheat available in skull melting.

## The Possibility for Solidification in the Absence of Contact with Molds

In terrestrial levitation experiments, extreme degrees of subcooling before solidification are often observed (23). Walker has achieved subcooling for a number of materials in glass lined crucibles. In some cases the degree of subcooling is believed to approach that at which homogenous nucleation occurs. The possibility exists that some materials may form new phases if solidified in the absence of heterogenous nucleation caused by crucible or mold contact. For example, a new phase of gallium denoted as Gallium 3 has recently been prepared in minute quantities at a temperature of -30$^{0}$ centigrade (24).

The possibility for forming glasses from materials which normally crystallize through heterogenous nucleation has been discussed in papers by Olsen and Happe (25). Since the nature of such products cannot be anticipated at present, it is clear that containerless solidification experiments must initially be proposed with emphasis upon obtaining basic information rather than with any attempt to anticipate commercial applications.

It has been suggested by Witt (26) that difficulty encountered in pulling thin filaments of single crystal material from melts in studies by Monsanto Research would be greatly relieved if it were possible to suspend a crucibleless melt of boron, for example, and apply forces to the melt which would oppose forces due to withdrawing a boron fiber at a rate allowing single crystal formation.

The possibilities for formation of near perfect spheres by solidification of melts under the sole action of their own surface tension has also been suggested.

## Shape Formation Through Surface Tension and Inertial and Electromagnetic Fields

Deeg (27) has suggested possibilities of fire polished glass surfaces for spherical or spheroidal surfaces which could be formed by centrifugal action in a freely suspended rotating melt. Rotations to produce an oblate spheroidal form of given eccentricity can be easily imparted to a floating mass by means of the orthogonal coil sets discussed in a following section

Alternatively, or, in conjunction with inertial forces produced by rotation, electrostatic fields can be applied to perturb the spheroidal shape. If the electric field at the surface of a conductor is represented by E, the local curvature imparted to the surface will be given by

$$\sigma\left(\frac{1}{r_1} + \frac{1}{r_2}\right) = p + \frac{E^2}{8\pi} \quad (\kappa - 1)$$

where $r_1$ and $r_2$ are the radii of the curvature in two orthogonal directions, p is the internal pressure, $\sigma$ is the surface tension, and $\kappa$ is the dielectric constant. Where only slight departures from spheroidal form are required, design of suitable electrodes to furnish fields to produce a desired shape may be feasible.

## POSITIONING AND HANDLING OF CONTAINERLESS MELTS – THEORETICAL AND EXPERIMENTAL STUDIES

A large number of the suggested new processes in weightless processing of metals and ceramics involve at some stage a floating molten mass out of contact with crucibles or molds. A floating mass of this type, held together solely by its own surface tension force and free to oscillate in shape, rotate and support internal fluid currents which might be driven by these or other applied forces, represents a phenomenon with which we have had little experience. Such phenomena, of course, are briefly encountered in shot tower processes and in free falling liquid streams but here the effects of air resistance and, usually, lack of time to establish equilibrium exist.

We have begun a study to investigate the physical problems associated with the melting, handling and solidification of such freely floating masses. The study of the basic physics involved in such processes leads quite naturally to a definition of the experimental facilities which will be required to handle a range of suggested processes. We have also begun the development of some new physical hardware concepts which will be required in such facilities.

### Shape Oscillations

The mathematical physics of small shape oscillations in a liquid mass under the sole action of surface tension and viscous and inertial forces was treated by Lord Rayleigh (28), and more recently by Chandrasekar (29). The extension of this work to include large oscillations and large viscosity have been made by Benedikt (30) and Reid (31). For reasonably small oscillations, Figure 1 gives the oscillation frequency and time decay constant for shape oscillations in which the shape is alternately a prolate and oblate spheroid. This is the simplest mode of oscillation. More complex shape oscillations can also occur; for a given material the oscillation frequency will be greater and the decay time shorter than for the mode for which Figure 1 applies. The mathematical expressions for the frequency and decay time for a given oscillation mode are available from the classical literature (32).

### Mass Limitations

Shape oscillations in free floating melts are to be expected whenever exciting forces are applied such as by means of radio or audio frequency fields used for position control. It is of course important to insure that no shape oscillation be initiated which can rupture the floating mass. The largest size mass which can be handled and kept intact thus depends upon the magnitude of position control accelerations which it is necessary to apply. These accelerations may range from $10^{-4}$g to $10^{-7}$g in practice as discussed below. For materials of reasonably high melting points, it appears that the upper limit to the mass which can be processed in a space facility will probably be determined by the maximum size of the available heating power source. For low melting materials, surface tension maintenance of mass integrity may enter as a limitation on mass. Simple calculations (33) indicate that masses of at least tens of kilograms can be considered even for the least favorable requirement. ($10^{-4}$g control accelerations)

## Rotations

For freely floating liquid masses which are put into rotation, various oblate shapes can be achieved by suitable choice of angular speed. For reasonably good conductors, these angular velocities can easily be imparted by application of rotating magnetic fields in an induction motor analogy. The rotating magnetic field would be produced by pairs of orthogonal coil sets phased in quadrature. These same coils can also be used for position and velocity control as discussed in the following. Shape oscillations will damp out within reasonable time periods as can be seen from Figure 1 and precision spheroidal shapes can be expected. Excessive angular velocities can of course lead to rupture of the liquid mass.

## Electromagnetic Positioning and Sensing

In this section I will summarize theoretical and experimental work which we have done on electromagnetic position sensing and control for floating spherical objects. We have also done limited work on electrostatic and magnetostatic position control. The mathematical solutions for the electromagnetic field induced within conducting bodies under the influence of alternating applied fields has been given in the physics literature for many simple configurations. The one of main interest to us is a solution given by Smythe (34), for a conducting sphere placed into a previously uniform alternating magnetic field. In using alternating magnetic fields for position control and sensing, nonuniform fields must be used. Nevertheless, Smythe's theoretical model gives a good base approximation for the magnetic dipole moment induced in the sphere. The force can then be calculated using this approximate dipole moment and the actual gradient for the nonuniform field employed. The magnetic vector potential $\vec{A}$ within the conducting sphere is found by solving the differential equation.

$$\nabla^2 \vec{A} = \mu\sigma \frac{\partial \vec{A}}{\partial t} \qquad \mu = \text{permeability} \quad \sigma = \text{electrical conductivity}$$

subject to the boundary condition that the field outside the sphere approaches the applied field at distances remote from the sphere and that the field is finite everwhere. For a sinusoidally oscillating field, we will write the vector potential time dependence as exp (i $\omega$t) so that

$$\frac{\partial \vec{A}}{\partial t} = i\,\omega\,\vec{A}$$

The current density within the sphere is given by

$$\vec{j} = -\sigma \frac{\partial \vec{A}}{\partial t}$$

and the magnetic field B is found from

$$\vec{B} = \vec{\text{curl}}\,\vec{A}$$

Figure 2 shows the variation of magnetic field along the sphere radius for various sphere conductivities and field frequencies. The graph is made dimensionless as discussed in the following.

The electromagnetic field is absorbed as it passes into the sphere and the characteristic length for this absorption (known as the "skin depth" $\delta$) is given in terms of the sphere permeability $\mu$, electrical conductivity $\sigma$ and the angular frequency of the applied field $\omega$ by the equation

$$\delta = (\mu\,\sigma\,\omega)^{-1/2}$$

The variation of magnetic field strength, electric current density and consequent forces and heating rates depend only upon the skin depth and the applied external field strength. Thus it is appropriate to plot results in terms of ratios of sphere radius to skin depth. This ratio ranges from 0.1 to 5 in the figure. This covers, for example, a 1 centimeter aluminum sphere at 10 kilocycles at the high extreme and molten glass of 1 cm radius at 10 megacycles at the other extreme.

The total force on the sphere can be computed in terms of the dipole moment from the eddy current distribution. However, since the body forces acting on the fluid within the sphere will generate internal fluid currents, we wish also to study the details of distribution of these forces within the sphere. Figure 3 shows the variation of radial body forces for various positions within a sphere over a range of ratios of skin depths to sphere radii. For good conductivity and high frequency, the force is concentrated near the surface of the sphere. These forces will give rise to circulating fluid currents within the sphere. If the sphere is immersed in a uniform oscillating magnetic field or one which varies only slowly with position, as would be created by a single pair of coils as shown in Figure 4, fluid currents will be excited which travel radially inward at the sphere equator and outwards to the poles defined by the coil axis.

For complete position control, three orthogonal sets of coils will be used which gives rise to a number of choices of modes of coil excitation. One scheme we have considered consists of an equal duty cycling of the three coil sets so that only one is excited at a given time for position sensing and control. If, on the other hand, three coil sets are excited simultaneously, more complicated current distributions within the sphere can be obtained as illustrated in the right hand portion of Figure 4.

These fluid currents generated by magnetostrictive forces may be very useful for stirring of floating melts just as this type of stirring has proven very useful in terrestrial experiments to obtain well homogenized alloys and dispersions. This is one possible answer to the question of how to stir melts without introducing heterogenous nucleation from the introduction of stirring rods, etc.

For electromagnetic fields having a significant gradient, such as can be obtained by differential excitation of a given coil pair, translational forces will be imparted to the sphere. For the case where only one member of a pair is excited, Figure 5 shows the manner in which acceleration of an aluminum sphere would vary with sphere position for a coil excitation of one ampere turn. We have experimentally verified these curves in the low force region which will be useful in the weightless space environment. Figure 6 gives experimental force measurements which we have made down to a level of five dynes on a sphere weighing $1.3 \times 10^4$ dynes, and a corresponding acceleration of $3.6 \times 10^{-4}$g. These measurements have been made by means of coils with horizontal axes and a one centimeter radius sphere suspended on a pendulum of length up to two meters. We have also made limited measurements for precision spheres free to roll on a precision glass tilt table and are currently developing other methods capable of measuring accelerations down to $10^{-6}$g. We have operated torsion balances in other experiments with sensitivities as low as $10^{-5}$ dynes, but have not as yet utilized this device in our electromagnetic positioning experiments.

## Laboratory Demonstration of Two-Axis Electromagnetic Sensing and Positoning Servo

We have prepared a film showing current activities in developing demonstration hardware based on the principles which I have described. The first scenes from the film (see Figures 7 and 8) show a general view of the laboratory setup and the two axis coil system for controlling the ball position laterally. A solid sphere of approximate 1 in. diameter is suspended from a long pendulum so that observable lateral translations occur when forces are applied capable of causing accelerations in the milligravity region. The next scenes from the film show that the ball is confined to stay within the potential well created by the four coils even in the absence of position and velocity detection and position control servo action. The coils are excited to a degree where the gravitational restoring forces due to the pendulum suspension are small compared to the electromagnetic position restoring forces. The shape of the potential well created between the coils depends upon the phasing of the alternating current to the various coils. The wells generally have a pincushion cross section and can be made to have a very low slope in the central region when opposite members of a coil pair are connected in phase. With the position sensing and position control servo actuated we see that the ball is not only confined within the potential well of the coils but is rapidly brought to the center of the well and its velocity relative to the coils brought to zero. Elimination of any velocity error relative to the space laboratory facility is important for those processes where it is desirable to completely eliminate position control forces during part of the process, such as for example solidification of melts into an accurate spherical or spheroidal shape.

The next scene shows control of position of the sphere by trimming the steady state excitation in the coil pairs. Here the trimming was carried out rather slowly to avoid initiation of position oscillations.

The next scene shows the manner in which the suspended sphere can be spun up by phasing the excitation of orthogonal coil pairs in quadrature. Here the sphere is copper and is supported by a ball bearing. Because of the bearing friction a large slip is encountered between the rotating field and ball. In the zero gravity environment, near perfect syncronization would be expected and field rotations of several cycles per second will give significant deformations into oblate spheroidal configurations for sizes in the range of one to several centimeter radius.

The next scene shows initial tests of an electrostatic positioning device. Here the sphere is surrounded by several pointed electrodes. Field strengths of several thousand of volts per centimeter were used with a water filled thin glass spherical shell of approximate 1 in. diameter. We can note that, even at the low temperatures involved here, corona discharge ultimately builds up a charge on the suspended sphere leading to erratic behavior. It should be noted, however, that in the zero gravity environment, much lower field strengths, on the order of volts per centimeter, can be contemplated.

## GENERAL REQUIREMENTS FOR SPACE EXPERIMENT FACILITIES

Each of the proposals for exploiting the weightless feature of the space environment in metallurgic and ceramic processing of course requires an individual study of facility requirements in terms of heating power, instrumentation, size of facility, etc. Since a large number of these suggestions involve the handling of a floating molten mass out of contact with crucibles or molds it is nevertheless possible to define, even at this stage,facilities which will be capable of accepting a large number of candidate new weightless processing experiments. We have begun a study for NASA to define the physical requirements for a wide range of potential new crucibleless melting and solidification experiments in order to define limits to the range of variables which can be handled in one or more facilities which may be practicable for early incorporation in the post Apollo program.

Some of the physical variables which are important in defining the required experimental facilities are summarized below:

| Process Variable | Facility Requirement |
| --- | --- |
| Melting temperature<br>Size of batch<br>Heating rate | Heating power |
| Requirements for vacuum or controlled atmosphere<br>Requirements for pre-melting of pre-cast specimens or for crucibleless mixing and reaction | Processing chamber and accessories, starting material, handling devices |

| | |
|---|---|
| Cooling rate<br>Solidification temperature<br>Processing time<br>Purity requirements<br>Requirements for absence of contact with crucible of melt during some part of the process | Position control, free floating volume |
| Requirements for stirring<br>Requirements for shaping or molding | Electromagnetic or electrostatic fields, provision for rotation of melt |
| Likelihood and nature of included bubbles | Requirements for stirring and bubble detection/elimination technique |

I should like to give a few examples of work we are doing to translate some of these rather general process requirements into a definition of the facilities required to handle a wide range of processes. The requirements on facilities imposed by position control, position sensing, heating, processing time, free floating volume required for the specimen, maximum permissible accelerations in terms of shape distortions, etc. are of course all related. We first discuss these requirements separately; however, in the course of a detailed discussion the interdependence of these requirements will become obvious and the region of intersection of the various experiment requirements in terms of facilities will, in most cases, define the required facilities within fairly specific limits.

## Positioning Requirements for Crucibleless Melting Experiments

### Type of Positioning Control

We have concentrated upon the study of positioning by means of applied electromagnetic fields. This includes not only electromagnetic fields which are driven at audio or radio frequencies but electrostatic and magnetostatic fields as well. For good conductors, position control by means of interaction between applied alternating fields and the eddy currents induced within the processed specimen is particularly convenient. Induced eddy currents can also be used to heat the specimen and control its temperature. In this section we shall discuss the range of frequencies and powers required for position control of free floating molten or solid masses.

For good conductors, eddy current position control at audio frequencies can be achieved without appreciable heating of the sample. If simultaneous eddy current heating is desired, higher frequencies can be used and the power used for heating is more than ample for position control of the specimen. For this type of process, position control is achieved by small differential excitations in coils on opposite sides of the specimen where the total eddy current power dispersion in the specimen can be held constant. Other types of processes can be considered where other means of heating are used.

Figure 9 shows the eddy current power absorbed by a free floating specimen when it is accelerated by an eddy current positioning device at a rate $10^{-6}$g ($10^{-3}$ cm sec$^{-2}$). This acceleration is characteristic of the lower limit which may be achievable in low altitude earth orbiting facilities unless compensation for decelleration due to air drag and gravity gradients is provided. The power requirement depends upon the sphere mass, density, electrical conductivity and driving frequency. It also depends upon the magnetic permeability of the specimen but our main interest is in molten materials whose temperatures will be above the Curie temperatures so that we may assume unit permeability. It would be possible to plot this figure with a dimensionless abscissa which is the ratio between the sphere radius and the skin depth to which the electromagnetic field penetrates. For facility definition it is preferable however to exhibit engineering parameters such as frequency, power and sphere size for specific processes. We see from Figure 9 that the minimum power required for positioning is linearly proportional to the sphere radius and depends drastically upon the conductivity of the material. For example, minimum position control power for a one centimeter aluminum or molten glass sphere at an acceleration of $10^{-6}$g ranges from $10^{-5}$ watts to 100 watts. For molten glass of relatively high conductivity the corresponding power required for position control drops to 10 milli-watts. The corresponding frequencies required for position control range from the low audio range for metals to hundreds of megahertz for molten glass of poorest conductivity.

For relatively small experiment vehicle carriers, such as the proposed dry work shop, astronaut body motions may occasionally impart accelerations to the vehicle approaching $10^{-4}$g for short time periods. For most processes, sufficient free volume can be provided surrounding the specimen being processed so that it can remain free floating without seeing accelerations of this magnitude. Since these accelerations will average out to zero over a time period on the order of a minute or less, it is highly likely that rigid process control with respect to the vehicle will not be required. At least for short processing times, the operation of such accelerating forces could easily be inhibited until process completion. If it is desired to provide rigid positioning of free floating objects with respect to the vehicle during accelerations as high as $10^{-4}$g, we can refer to Figure 10 for the required positioning powers. For the metals in the range up to ten centimeter radius the positioning powers are essentially negligible (less than one watt). For high conductivity molten glass the power requirement ranges up to only ten watts. For poorly conducting molten glass, required positioning powers can reach the multi kilowatt region and hence it appears that eddy current position control is not a likely candidate in this extreme case.

For material conductivities, sphere radii, and driving frequencies such that the skin depth of penetration exceeds the sphere radius, a change in driving frequency will cause the acceleration and power dissipated to vary in the same proportion. Thus increasing the frequency so as to double the acceleration will also double the power dissipation. Curves showing the manner in which the acceleration and power dissipation vary with frequency have been prepared by Fromm and Jehn (35). These curves show that for frequencies and conductivities such that the skin depth is a small fraction of the sphere radius the power dissipation increases with frequency more rapidly than acceleration. For the metals, positioning with negligible heating at low frequency is relatively simple. For a very poor conductor such as molten glass, an increase in frequency to at least the high audio range and even into the tens of megahertz range is required and hence eddy current heating cannot be avoided. We have displayed the dependence of power dissipation, normalized per unit sphere surface area, and acceleration as a function of driving frequency for metals in Figures 11 and 12.

Here we see that the choice of frequency for a positioning facility can be made conveniently in the audio region if the specimen is heated by some means other than eddy currents. In practice, we can select a frequency somewhat arbitrarily, such as ten kilohertz, for which requirements for electronic circuit design are extremely simple. The actual positioning forces obtained at a given driving field strength will then of course depend upon the resistivity and size of the material sphere being processed. In the servo positioning device which we are developing, the exact restoring force per unit position error is not particularly critical. Moreover, the servo loop gain can be varied quite easily, if desired, for different specimens by turning a knob to a precalculated position. In practice, such an adjustment would probably not be made unless the material resistivity varied extremely from one specimen to the next.

As a matter of interest, and since it plays the fundamental role in determining both the positioning forces and power dissipation, we show the skin depth as a function of frequency in Figure 13. Depending upon the frequency and conductivity we see that the skin depth can range over 7 decades of variation, thus the ratio of skin depth to sphere radius can vary from values much less than unity to values much greater than unity for cases which will be of interest. This is in contrast to work in terrestrial levitation experiments where skin depths greater than the sphere radius are of little interest since they in general do not provide sufficient positioning force to levitate the material in the one g environment. The greater freedom of choice of frequency and skin depth for the case of materials which are processed in the zero gravity environment allows for eddy current heating which can be adjusted independently from the requirement for positioning.

An alternative way for position control of a freely floating molten or solid mass is the use of electrostatic fields. An electrostatic field introduced into the space around a floating object will induce an electric dipole moment in the specimen. This induced electric dipole moment will then interact with any gradient or nonuniformity in the applied field to produce a translational force. If we denote the position coordinates as $x_1$ $x_2$, $x_3$ and the electric field components as $E_1$, $E_2$, $E_3$, the components of the force are given by

$$F_\mu = \frac{\partial E_\mu}{\partial x_\nu} \, kE_\nu$$

sum over $\nu = 1,2,3$ for $\mu = 1,2$ or $3$
k = constant involving the dielectric constant

The introduction of a dielectric or metal specimen into the space will perturb the field from its previous value. The corresponding induced electric dipole moment for spheres and many other shapes of interest has been derived in some of the classical literature on electric potential theory. For example, the dipole moment induced in a pyrex glass sphere of one centimeter radius by a field of one KV $cm^{-1}$ will give rise to an acceleration of $2 \times 10^{-4}$g if the field strength changes by 30% over a one cm interval. Such a gradient can easily be provided from, for example, six electrodes surrounding the suspended specimen in opposing pairs along each of three rectangular axes. For accelerations of $10^{-6}$g, field strengths of only tens of volts per centimeter will be required. Although electrostatic field position control is in principle no more complex than eddy current positioning such as we have discussed, it has some inherent problems if used in conjunction with materials which outgas. At high field strengths, corona discharge may be encountered. For the case of specimens which outgas metal vapors, plating and consequent shorting of insulators and electrodes may be encountered unless adequate baffle systems can be provided. It appears that, at least for glasses, these problems can probably be solved and that in this sense there is an overlap in the region of applicability of electromagentic and electrostatic positioning.

### Position Sensing

A number of position sensing schemes are available which can be used for position control or handling of free floating solid or liquid materials. Besides the eddy current position sensor which we have developed and applied to sensing of metallic objects, one may also consider bolometers or other heat sensing detectors or changes in electrostatic capacitance. The latter would be a natural solution in the case of an electrostatic position control device.

Another possibility is optical sensing, either by emitted radiation from a hot object, by interception of optical light beams, or visual or photographic observations. It is expected that visual observations of specimens during processing should be provided wherever possible, particularly in pilot experiments.

Any of the above position sensing methods, except photographic, can be used to actuate a position control servo in the same manner as is done in our demonstration electromagnetic device. It is quite likely that none of the above methods will be applicable to all processes but that each will have its own domain. It appears that these domains overlap. For many processes, either the eddy current position sensor or the bolometer position sensor will be adequate. For samples of very high resisivity which must be positioned at temperatures too low for detection of emitted radiation, the electrostatic or optical methods can be considered. Normally, however, positioning of these specimens can perhaps be performed mechanically when they are removed from the processing chamber after cooling.

### Heating and Temperature Control

The minimum heating power which must be provided is that necessary to furnish surface radiation loss from the specimen. If a controlled atmosphere is utilized, additional power will be conducted away by the gas. In this connection it must be noted, however, that normal convection due to buoyancy of the heated gas will be absent and that under these conditions, the gas will act as a good insulator. For many materials, including most metals, the choice of heating methods can be made independently of the choice for position control. For materials of very high resistivity such as glasses, the electromagnetic positioning can give rise to eddy current heating dissipations which can become significant so that it may be advantageous to consider RF heating, at least for things such as molten glass having reasonably good conductivity. One might be led to think, conversely, that the choice of eddy current or RF heating will lead to unavoidable positioning forces. However, if RF heating is provided by pairs of coils symmetrically disposed on either side of the specimen, no net translational force will be applied to the specimen when the coils are equally excited. With such an arrangement if it is desired to impart a position control force, small differential excitations can be introduced into the coil excitations through a servo loop actuated by position or velocity errors in such a way that the total power dissipation in the specimen is unchanged. The specimen temperature can be controlled by raising or lowering the total coil excitation power.

Figure 14 simply illustrates the surface radiation loss, or minimum heating power required to achieve the melting or transition temperature for several materials of interest. By way of illustrating the relation between the heating power requirement, if this is provided by eddy currents, and the eddy current positioning requirements discussed earlier, we may consider the example of lead telluride at its melting point. This requires a minimum power dissipation in a one centimeter radius sphere of 50 watts. Referring back to Figure 11 we see that this requires a driving frequency of 300 kilohertz at 300 ampere turns, corresponding to a maximum acceleration of .04 g if all of the power is furnished by a single coil. Any lower value of position control acceleration can be provided by shaping the driving power between two coils, one on either side of the specimen.

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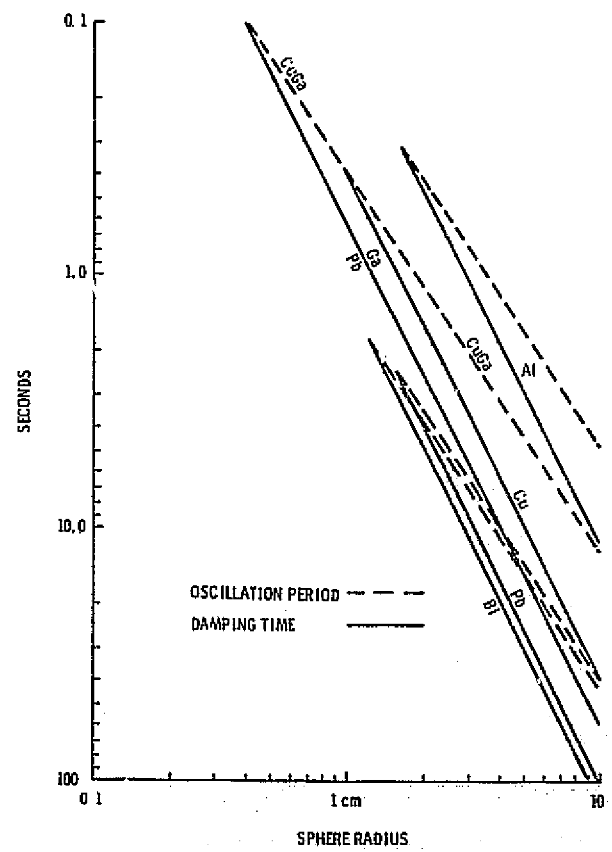



Figure 1 Shape Oscillation Periods Free Floating Melt

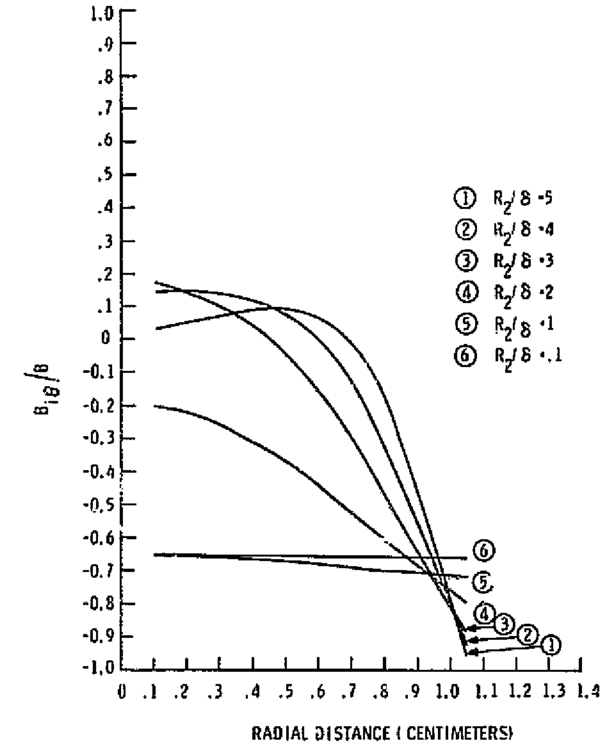



Figure 2. $\theta$ Component of Magnetic Field per Unit Magnetic Induction in Aluminum Sphere of Radius $R_2 = 0.4125$ Inch at Colatitude $\theta = 45^o$ Showing Penetration of Field into Spheres as a Function of Skin Depth

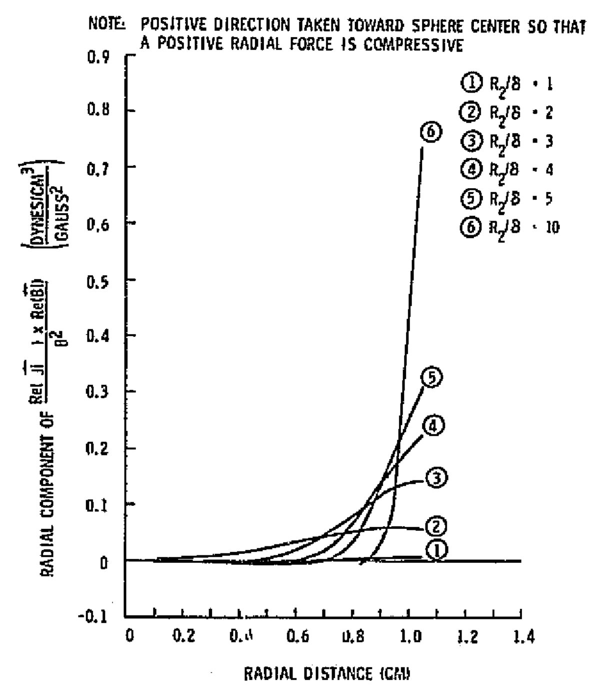
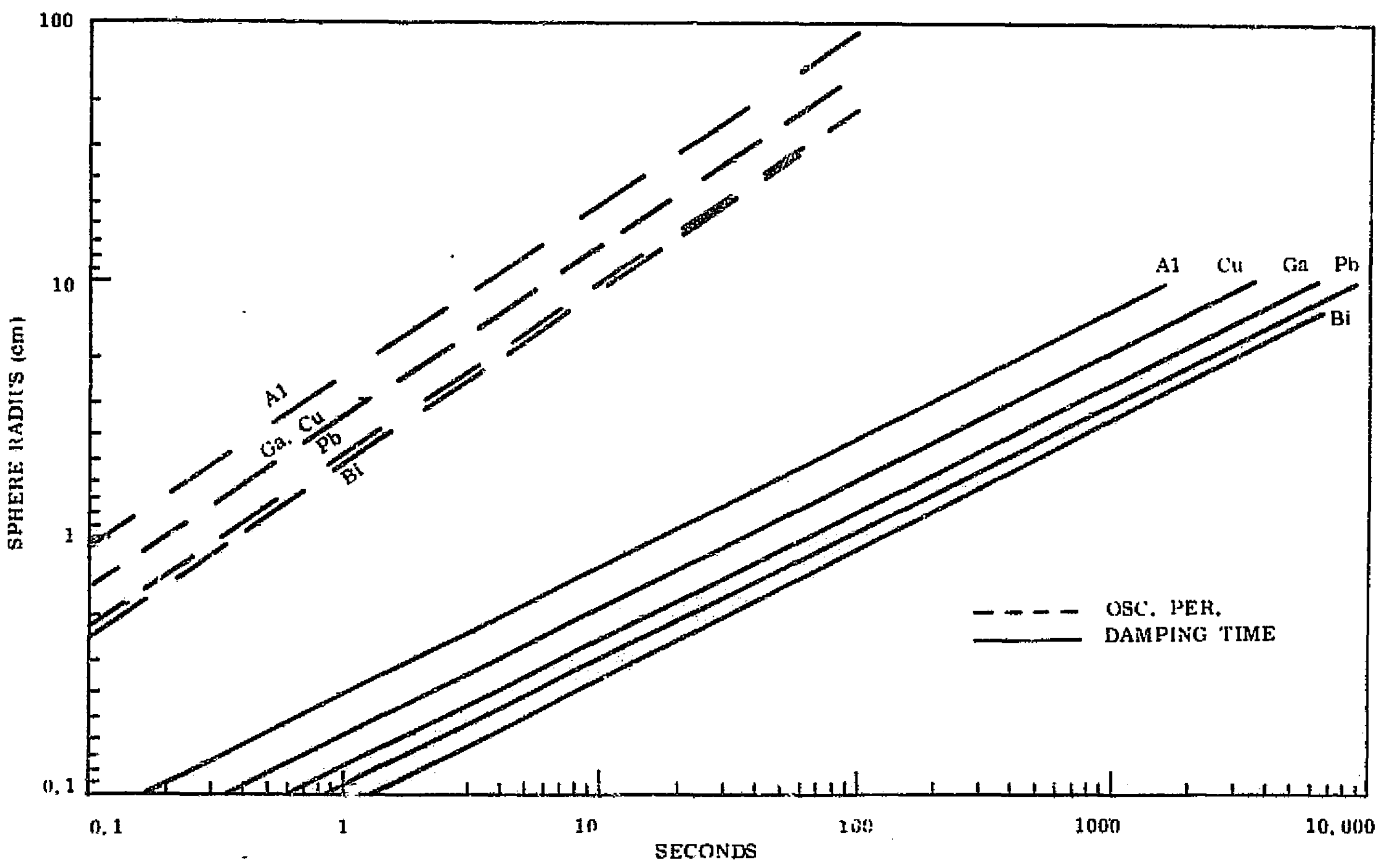



Figure 3. Radial Component Force/Volume per Unit Magnetic Induction Squared for Aluminum Sphere $R_2$ $R_2 = 0.4125$ Inch at $\theta = 45^o$ as a Function of Skin Depth

# ERRATA

"Techniques and Examples for Zero-G Melting and Solidification Processes" by R. T. Frost

Figure #1 in the proceedings of the 7th Space Congress should be replaced with the figure below.




Shape Oscillation Periods Free Floating Melt

Figure 1

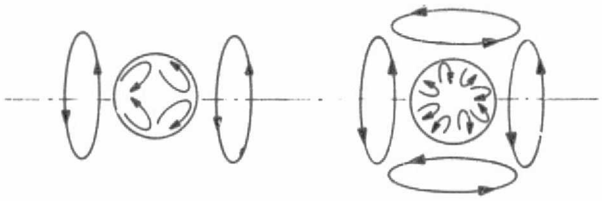


Figure 4. Fluid Currents Excited by Magnetostriction

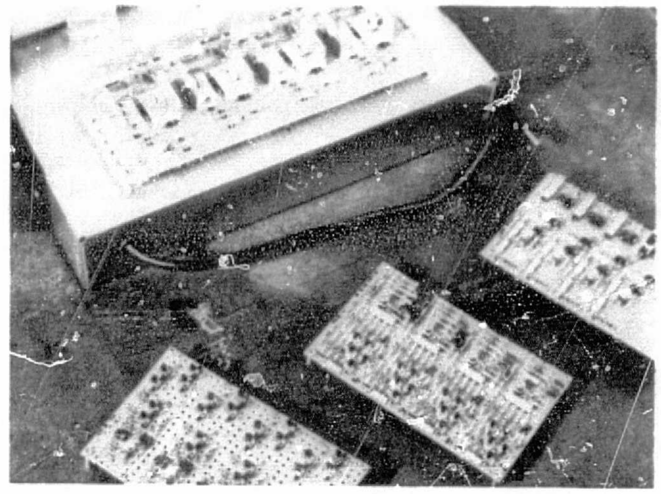


Figure 7. Position Sensing and Control Electronics

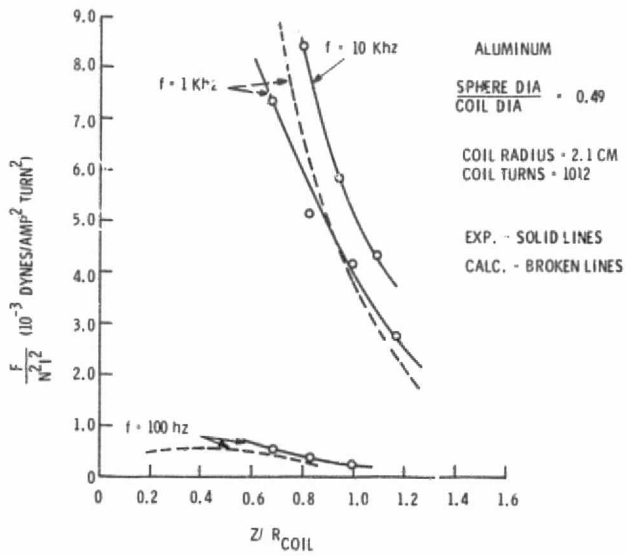



Figure 5. Force as a Function of Position

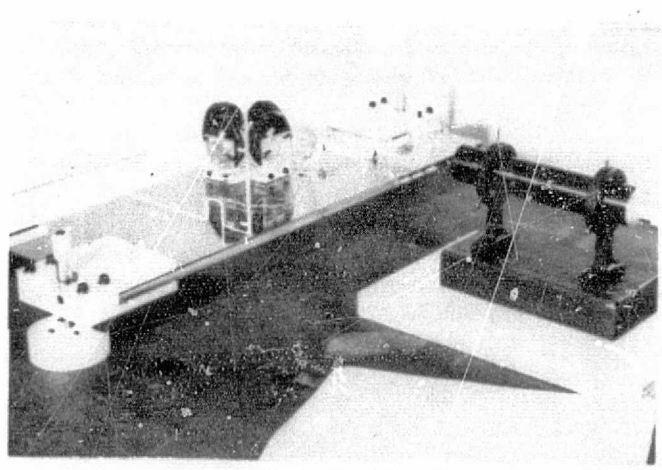


Figure 8. Positioning Coils, Pendulum Suspension and Instrumentation

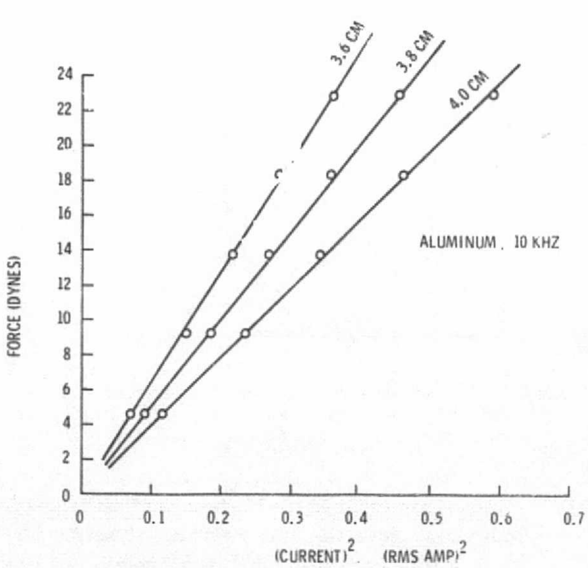



Figure 6. Experimental Force Measurements

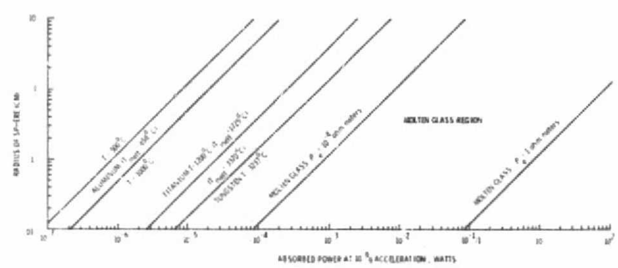


Figure 9. Minimum Power Absorbed with $10^{-6}$g Acceleration Applied to a Sphere

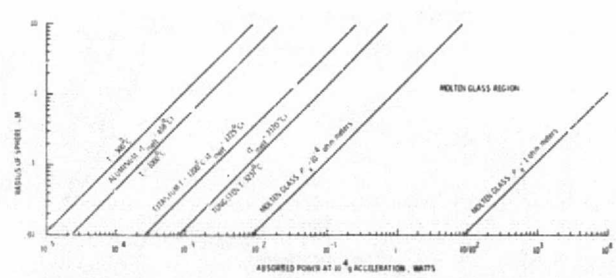


Figure 10. Minimum Power Absorbed with $10^{-4}$g Acceleration Applied to a Sphere

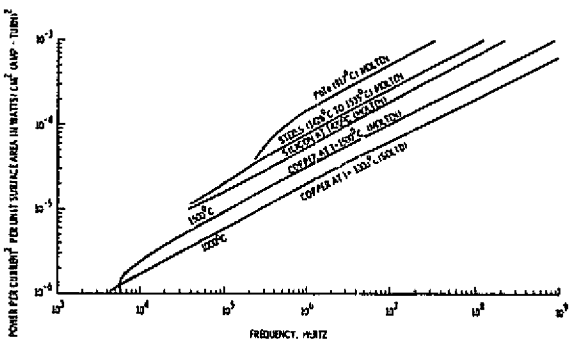


Figure 11. Power Absorbed by a Sphere Radius 1 cm (1 amp turn coil of radius 1.905 cm)

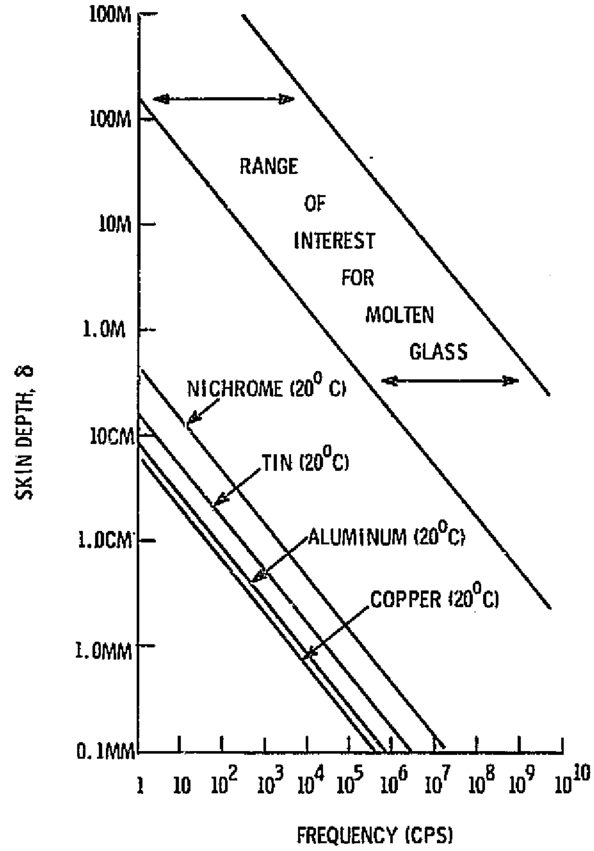



Figure 13. Skin Depth vs. Frequency for Several Common Metals and Molten Glass

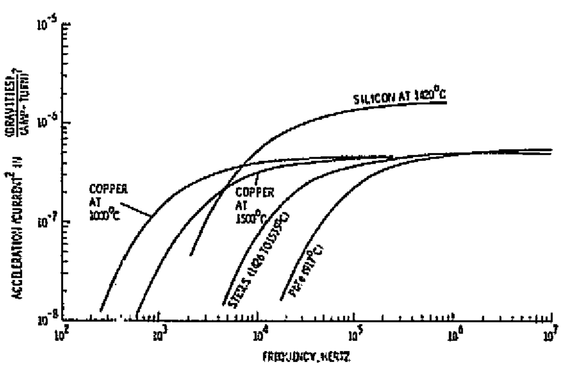



Figure 12. Acceleration/Current$^2$ Imparted to a Sphere of Radius 1 cm (1 amp turn coil of radius 1.905 cm)

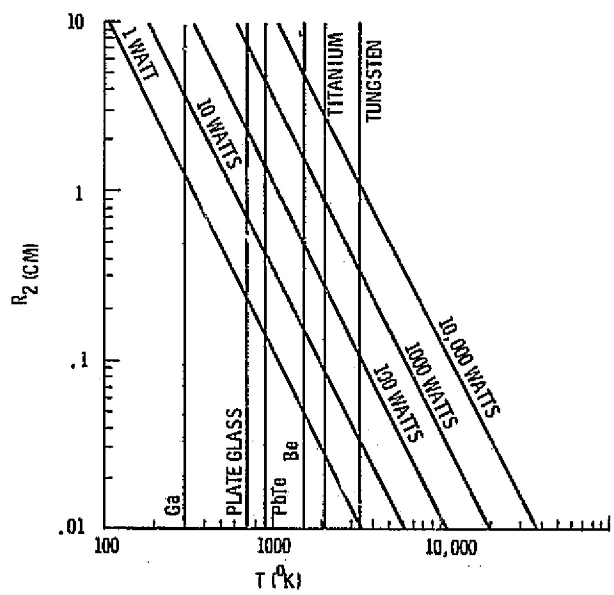



Figure 14. Surface Radiation Loss for Unit Emissivity

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# SELECTED EXAMPLES FOR SPACE MANUFACTURING PROCESSES, FACILITIES, AND EXPERIMENTS

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ABSTRACT

The unique effect of the orbital zero- and low-g environment upon the behavior of liquids offers the potential of new material processing techniques not feasible under terrestrial conditions. A number of promising processes and the related product capabilities are discussed in detail. On the basis of an evaluation of process effectiveness and facility requirements, an example for a potential three-phase space experiment program is presented.

## INTRODUCTION

The objective of this paper is (1) to identify promising space manufacturing processes on the basis of the potential and limitations of the g-environment and (2) to define the related operational and tooling requirements and their integration into a meaningful space experiment program.

Individual line items of discussion are:

1. Low-gravity environment and its effect upon matter.
2. Definition of basic zero-g phenomena and their application in processing techniques.
3. Discussion of individual processes and their product potential.
4. Assessment of process priority for space experiments.
5. Experiment facility requirements.
6. Example experiment program.

In view of the wide scope of the discussion, it goes only to such depth as required for the support of reasoning and conclusions. Detailed theoretical treatments as well as the discussion of specific materials are omitted, since they have been documented before, particularly in Ref. 1 and 2.

As has been pointed out earlier by Wuencher in Ref. 1, 2, and 3, the sustained zero- and low-g condition encountered in orbital systems is the only environment which is truly unique, since it can be reproduced under terrestrial conditions only as a transient effect, too short for practical applications. Other useful orbital environments, such as high vacuum, low temperature, solar heat, high energy radiation, and the perfect black-body condition of deep space are not as unique, and are therefore confined to secondary applications, wherever beneficial, in conjunction with zero- or low-g processes.

In view of the dominant role of the g-environment, its nature and effects will first be analyzed in some detail.

## THE ORBITAL G-ENVIRONMENT

Even though we often refer to "zero-g manufacturing," it is apparent that absolute zero-g exists only under very rare conditions and that in most cases we deal rather with certain low-g levels, depending on the orbital characteristics of the vehicle and the specific position of our manufacturing operations with regard to the vehicle.

The term "g" as used in this context should be clearly distinguished from the g representing the acceleration due to earth gravity, which only for the purpose of this clarification we may define as $g_E$. The g used in such expressions as "zero-g" or "low-g" defines a g-level as it is commonly used in dynamics and aerodynamics. By relating g to $g_E$ it becomes a dimensionless value.

For a more accurate definition of the dimensionless g-level, we may consider a particle P of mass in the gravitational field. The particle is acted upon by the gravitational force $F_{gE}$ and by applied forces $\Sigma F_{ip}$, with a resultant inertial acceleration $a_p$, as identified in Figure 1. The g-level or g, as used in the discussion, is then defined by

$$g = \frac{\Sigma F_{ip}}{m g_E} \qquad (1)$$

as the sum of forces applied to P divided by m to make it an acceleration and by $g_E$ to make it dimensionless (Ref. 4).

*Note: Most of the studies in this paper were carried out under contract with the Manufacturing Engineering Laboratory, Marshall Space Flight Center

The change of the gravitational field of the earth as related to altitude from the earth's surface is shown in Figure 2. At the mass center of a vehicle orbiting at a given altitude, the downward gravitational force is balanced by the centrifugal force, except for the rather minute effect of vehicle drag. At this point the g-level, as defined above, is for all practical purposes zero. For any other point of the vehicle it can be shown that the g-level in radial direction is given by

$$g = \frac{\Delta F}{m} = -2w^2 \Delta r \qquad (2)$$

Where w is the orbital rate and $\Delta r$ the radial distance from the mass center. (Ref. 4.) Above the mass center, the distances $\Delta r$ at which certain g-levels are encountered are as follows.

| Distance $\Delta r$ (ft.) | g-Level |
|---|---|
| 0.87 | $10^{-7}$ |
| 8.7 | $10^{-6}$ |
| 87 | $10^{-5}$ |
| 870 | $10^{-4}$ |
| 8,700 | $10^{-3}$ |
| 87,000 | $10^{-2}$ |

Coriolis accelerations would also add to these apparent g-levels.

These g-levels acting upon an object will cause it to drift in relation to the vehicle. The average drift distance d during one orbit is

$$d = -12\pi r_o = 37.68\ r_o \qquad (3)$$

in which $r_o$ is the starting point above the orbital path (Rheinfurth, Ref. 1). The minus sign indicates that for positions above the orbital path, the object is drifting backwards and below the orbital path, forward.

Regardless of its position or movement, the object is further exposed to the gradient of the earth's gravitational field. The resulting gravity gradient across the object is proportional to its size and is, for the altitude regime of near-earth orbital operations, of the order of $10^{-7}$ g per foot in the vertical (earth-radial) direction and approximately $3 \times 10^{-8}$ g per foot in the horizontal direction.

## EFFECT OF ZERO-G UPON MATTER

The most apparent effect of zero-g environment upon matter is the absence of relative mass acceleration, commonly referred to as weightlessness. This not only eliminates the need for support of solid or liquid matter, but also precludes any relative motion in fluids, due to differences in density, resulting in the absolute stability of liquid-solid, liquid-liquid or liquid-gas mixtures and the absence of thermal convection.

The effect of zero-g upon the intrinsic properties of matter is illustrated in Figure 3. In the solid state, the properties are for all practical purposes unaffected by g, since the intrinsic bonding energies surpass the g-force by many orders of magnitude. As soon as we enter the liquid state, the intrinsic properties, identified by cohesion and surface tension, are in the same magnitude regime as g. Consequently, under terrestrial conditions, the behavior of liquids is determined by the interaction of intrinsic energies and gravity. As g is reduced, the intrinsic properties become more dominant until under zero-g the characteristics of liquids or fluids in general are solely determined by their intermolecular forces.

The primary effects of low-g on matter are therefore defined as the absence of buoyancy, the absence of gravity-induced convection, and the unrestrained interaction of intermolecular forces. All these phenomena are only effective in the liquid, or more generally speaking, fluid state, and zero-g manufacturing is carried out exclusively in the liquid state of matter.

## BASIC PROCESSING PHENOMENA

In most manufacturing processes, several liquid-state phenomena are applied in various combinations. To avoid repetitious discussion, we may first define these basic phenomena and their typical applications.

### 1. Absence of Buoyancy

The most obvious application of the absence of buoyancy and the resulting stability of mixtures is the liquid-matrix processing of materials of different density. This comprises liquid-solid, liquid-gas, and liquid-liquid mixtures.

Liquid-solid mixtures find primary application in the casting of composites, particularly metal-matrix composites. Under terrestrial conditions, the liquid-matrix preparation of composites is limited to liquids of high viscosity, such as polymers. Metal-matrix composites are exclusively produced in the solid state, in view of the extremely low viscosity of molten metals. Solid-state processes have serious limitations with regard to matrix continuity, reinforcement integrity, and the resulting material properties. They further are limited to shapes dictated by the necessary unidirectional reinforcement orientation. Preparation in the liquid-matrix state, possible only under low-gravity conditions, not only eliminates all these constraints, but also costly secondary fabrication, since composite preparation and casting of a complex end-product can be carried out in one single operation.

While composite castings primarily involve fibrous reinforcement, there are several applications for mixtures of liquids with fine particles. One is the casting of dispersion-stabilized alloys either as end products or as ingots for secondary terrestrial fabrication. Evenly distributed fine particles may be further used as nucleation sites during solidification, resulting in fine-grain castings with superior mechanical properties. Fine particles may also act as nucleation sites for the formation of gas bubbles and foams, as will be further discussed in connection with related processes.

By proper temperature and pressure control of the liquid, finely dispersed particles may also act as nucleation sites for vaporization and the formation of gas bubbles as foams. Metal particles in a low-melting dissimilar metal matrix may further permit an extension of alloy formation by almalgamation or the preparation of alloys at moderate temperatures.

The application of liquid-liquid mixture stability has so far been limited to multiphase metals and alloys. In alloying, it prevents or reduces segregation between elements of different density and permits the preparation of supersaturated alloys. Unique alloy systems for specific applications may further be obtained from metal combinations which exhibit liquid-phase immiscibility. The application of liquid-liquid mixture stability in chemistry, even though of considerable potential, has not yet been evaluated.

Liquid-gas mixtures comprise two types: liquid continuum and gas continuum. So far, only the liquid-continuum variety has been pursued. It consists of a liquid matrix, such as a molten metal, and more or less finely distributed gas bubbles. The stability of this mixture requires temperature homogeneity. The objective are materials of reduced or variable density. In the gas-continuum variety, the liquid is finely distributed in the form of microspheres, much like a fog, and unique homogeneous or heterogenous materials may be obtained by condensation or deposition of single or multiple-phase mist on a permanent or disposable substrate.

## 2. Absence of Gravity-Induced Convection

The term "absence of convection" as used here refers to internal motion resulting from the combined effect of gravity and density differences produced by thermal gradients. While there are other sources of convection, such as variable surface tension or nonuniform thermal expansion, the gravity-induced convection is of substantially greater magnitude, so that under zero- or low-g, internal motion is reduced to a minimum. Internal motion is of prime concern in the process of solidification for two reasons. (1) Motion enhances nucleation and is therefore undesirable in all processes of crystallization control, such as the growth of single crystals or whiskers, directional solidification, or suppressed crystallization. (2) Convective currents may induce imperfections during crystal growth, such as dislocations, and impair the properties of the end product. Consequently, the absence of gravity-induced convection permits a control of crystal formation and material perfection not attainable under terrestrial conditions.

There are cases, however, where convection is desirable, particularly for the removal of gases evolving internally from a molten material. In the absence of gravity, the movement of such gases to the surface may be accomplished by localized surface-tension-induced convection. The advantage of such an induced process is its accurate controllability. In other words, in the gravity-free environment, we can apply such processes wherever and whenever we see fit, in contrast to the gravity environment, which we cannot turn off.

## 3. Undisturbed Intermolecular Forces

The most pronounced characteristic of liquids in a gravity-free environment is the undisturbed action and interaction of molecular forces.

In the continuum or bulk liquid, the intermolecular, i.e., the attractive and repulsive, forces are balanced. There is no free energy which could act upon the material or be acted upon by induced forces. Only by induced relative motion do momentary unbalances occur, whose total effect is sensible as "internal friction" or viscosity.

Viscosity of molten metals is extremely low, while it is higher in liquid nonmetallic inorganics such as oxides. Consequently, oxides are less sensitive to motion during crystallization, so that nucleation can be completely suppressed even at slow cooling rates (formation of glasses).

As we approach the surface, the intermolecular balance of forces is disturbed in one direction with a considerable increase of free energy. The total free energy of the surface region is referred to as interfacial tension, or, in the case of the liquid-gas interface, as "surface tension."

Surface tension produces pressure in the bulk, whose magnitude is inversely proportional to the radius of surface curvature according to the relationship

$$p = \frac{2\sigma}{r} \tag{4}$$

A liquid will always assume the geometry of minimum free energy, which, under dimensional constraints, represents a finite curvature and bulk pressure. In zero-g, the undisturbed liquid will assume perfect spherical shape. If due to some induced disturbance the curvature is nonspherical, we have to introduce two orthogonal radii, and relationship (4) is modified to

$$\Delta p = \sigma\left(\frac{1}{r_1} + \frac{1}{r_2}\right) \tag{5}$$

Surface tension $\sigma$, as used here and later, is more accurately the interfacial tension between the liquid and gas phase, identified by $\sigma_{LG}$. There are likewise interfacial tensions $\sigma_{LS}$ and $\sigma_{SG}$ for liquid-solid and solid-gas contact. The force balance of the contact point, where liquid, solid and gas meet is defined in Figure 4 and represented by the relationship

$$\sigma_{SG} = \sigma_{LS} + \sigma_{LG} \cdot \cos \beta \qquad (6)$$

For a finite contact angle $\beta$, the liquid will only spread out until uniform curvature has been attained. If $\beta$ is zero, Equation (6) is modified to

$$\sigma_{SG} \geq \sigma_{LS} + \sigma_{LG} \qquad (7)$$

and spreading is essentially unlimited; theoretically, the rate of spreading is determined by the difference between the two sides of the equation. In reality, the rate of spreading is affected by a number of secondary factors, e.g., shear forces such as a solid-surface roughness, which may be combined into a "spreading factor", best determined experimentally.

## Application of Low-G Phenomena in Processes

Specific effects of the three basic zero-g phenomena discussed are achieved by the introduction of certain controls. These controlled effects are the basis of all zero-g manufacturing processes.

Table 1 identifies the basic means of control and the resulting basic process concepts or products for each of the three zero-g phenomena. The table is arranged in two sections: the first comprises all techniques of processing in the liquid state; the resulting products may be either solids or liquids. In the second section, the prime zero-g effect occurs in the liquid-solid interphase, i.e., during solidification; all products consequently are solids.

The purpose of Table 1 is to give a first-order overview of the primary application of the low-gravity environment in various processes and products. While it identifies the methods of control only in generic terms, there are various modifications and combined applications for specific processes and products. Likewise, the zero-g phenomena may be applied in various highly effective combinations. The contact-free formation of a sphere, for instance, as a basic process employs only the intrinsic intermolecular forces without any controls. The mechanical properties may, however, be improved by the addition of strengthening fibers, involving the phenomena of mixture stability. The microstructure of the composite sphere-matrix may further be improved or customized for specific applications by various methods of solidification control.

## DISCUSSION OF SELECTED PROCESSES

A considerable number of processes and products has been suggested over the past few years (Ref. 1, 2, 3, and 5). Some of these are of a basic nature permitting a wide spectrum of modifications; they have, therefore, a considerable growth potential. Others are more specialized, often representing highly sophisticated concepts. The description of all these processes would exceed the scope and the objective of this paper. Rather, a limited number of typical processes has been selected, whose discussion will convey a fairly complete picture of the potentials of space manufacturing and, at the same time, identify the criteria and requirements for effective space experiments. The following processes will be discussed.

1. Production of spheres
2. Liquid forming
3. Thick-wall hollow spheres
4. Thin-wall hollow spheres
5. Flat membranes
6. Foams and cellular materials
7. Composite casting
8. Dispersed particle castings
9. Supersaturated alloys
10. Thermosetting alloys
11. Containerless melting of high-temperature alloys
12. Single crystal growth
13. Amorphous materials
14. Unit separation

In examining this list it can be observed that the prime characteristic of the first five processes is the product shape, generated without tooling contact by controlled intermolecular forces, or more accurately, interface energies. The same forming principle applies to the formation of the foam cells in process 6, even though the macroscopic end product must be classified as a material. The remaining products are primarily materials, whose capabilities are characterized by unique or superior properties. Of these, 7 through 10 are typical mold-casting processes, so that both material processing and end product forming can be accomplished in one single operation.

### 1. Production of Spheres

The processing of spheres is discussed in more detail, since it represents the basic shape of liquids in zero-g and since its criteria, problems, and procedures are typical for many other processes.

Process Discussion — The accurate spherical shape is generated in the liquid state by interface energy only.

The equilibrium between internal pressure, environmental pressure and surface tension has been defined in relationship (4) as

$$\Delta p = \frac{2\sigma}{r}$$

In numerical dimensions (dyn, cm, kg) this is approximately equal to

$$\Delta p = \frac{2\sigma \cdot 10^{-6}}{r} \quad (\mathrm{kg/cm^2}) \tag{8}$$

In the process of formation of the sphere from a non-spherical shape, the deformation-resisting forces are inertia and viscosity. However, in comparison with surface tension and inertia, viscosity can be neglected as indicated by the following calculated data for the transformation from a liquid cylinder to a 10 cm diameter sphere.

| Forces/Area (dyn/cm$^2$) | Water | Copper |
|---|---|---|
| Surface Tension | 14.6 | 220 |
| Viscosity | 0.003 | 0.013 |
| Inertia | 7.3 | 110 |

As illustrated in Figure 5, the inertia force is highest at the beginning of the forming process and becomes zero at its conclusion, while the surface tension force is essentially constant. The time required for the transformation is defined by the relationship

$$t \simeq \frac{1 + \sqrt{1 + \frac{4\sigma\rho R}{\mu^2}}}{2 \frac{\sigma}{R\mu}} \tag{9}$$

$\rho$ = density
$\sigma$ = surface tension
R = radius
$\mu$ = viscosity

which may for most liquids be simplified to

$$t \simeq \left(\frac{\rho}{\sigma}\right)^{1/2} R^{3/2} \tag{10}$$

The formation time is therefore in close approximation, defined by density, surface tension, and sphere size. The transformation is extremely fast, as evidenced by the following data.

| Liquid | Time (Seconds) | |
|---|---|---|
| | D = 10 cm | D = 1 cm |
| Water | 3.7 | 0.117 |
| Copper | 2.84 | 0.09 |

These calculated values are in perfect agreement with measurements made in free-fall experiments (Ref. 6 & 7).

It is apparent that the accelerated mass does not come to a stop after these times, but rather continues to oscillate around the spherical shape. As the initial nonspherical shape before release represents a potential energy, we may regard these oscillations as a continuing alternation between the potential and kinetic energy state, as illustrated in Figure 6.

The frequency f of these oscillations and the time $\tau$ required for the initial amplitude to decay to 1/e are represented by the relationships

$$f = H_f \sqrt{\frac{\sigma}{\rho}} \cdot D^{-3/2}$$

$$\tau = H_\tau \frac{\rho}{\mu} \cdot D^2 \tag{11}$$

in which H is a constant representing the harmonic order of the oscillations. For the simplest and most common oscillatory mode, the constants H amount to

$H_f = 1.273$

$H_\tau = 0.05$

It can be seen from relationship (11) that, with regard to active intrinsic material properties, the frequency is determined by surface tension only and the damping time by viscosity.

The high dependency of oscillation damping time upon sphere diameter is illustrated in Figure 7, in which the time to dampen to 10 and 1% of the initial amplitude is plotted over sphere diameter for water and for two metals of low and high surface tension. The damping time to 1% for a 10 cm diameter iron sphere is in the order of one hour, in contrast to 10 seconds for a sphere diameter of 0.5 cm. This implies that the accuracy of the end-product sphere can be measured by the waiting period from deployment to solidification. The magnitude of the initial amplitude depends entirely on the method of deployment.

The ultimately attainable accuracy, however, is limited by the distortion due to the earth-gravity gradient, which varies with the fourth power of diameter. Typical values (aluminum) are as follows.

| Sphere Diameter | Deviation |
|---|---|
| 2 cm | $10^{-9}$ cm |
| 10 cm | $10^{-7}$ cm |

This accuracy exceeds present terrestrial capabilities by at least three orders of magnitude.

Methods — There are two basic methods of sphere manufacture, illustrated inFigure 8.

Method 1

a. Deployment and growing to desired size with material supplied from a melting chamber and fed by a controlled pressure differential between melting and processing chamber (position A).

b. Detachment from the deployment nozzle by appropriate nozzle motion or by ultrasonic vibrations.

c. Holding in the center of the processing chamber (position B) by means of the position control coils P for the period of oscillation damping and solidification.

Method 2

a. Deployment of a solid, preshaped ingot in the center of the position control system (position B).

b. Melting by induction heating.

c. Oscillation damping and solidification.

While method 1 is designed for the consecutive manufacture of several spheres, method 2 may be preferable for single experiments. In both methods the sphere temperature has to be maintained in position B, either by induction heating or by radiation from the chamber wall.

Applications and Capabilities — So far, three types of potential applications have been defined:

1. As end products, such as bearing balls. Attractive properties are high dimensional accuracy, high surface finish, & microstructure homogeneity. Mechanical properties may be enhanced by fiber reinforcement (composite material) and/or by induced fine-grain solidification (process 8).
2. As ingots of metal matrix composites, or various types of alloys produced by other processes, or for glasses (process 13).
3. As initial shape for further liquid-state processing.

In spite of the attractive properties, the use of spheres as end products is limited. Spherical ingots, however, have a wide spectrum of applications in connection with other processes (Wechsler, Ref. 2). In addition, as the basic shape of liquids in zero-g, the sphere will serve as the standard test sample in the development of manufacturing techniques and tooling.

## 2. Liquid Forming

The reverse of the sphere formation from a nonspherical liquid is the deformation of a liquid sphere into a specific shape by means of contact-free induced forces, such as controlled electromagnetic fields or inertial forces (spinning). The required deformation force has to equal the total deformation-resisting force, represented in general terms by

$$F_{Deform} = F_{Surf.\,Tens.} + F_{Pressure} + F_{Inertia} \quad (12)$$

Upon arriving at the end shape, an equilibrium of forces has to be maintained to the time of complete solidification, which is defined as

$$F_{Hold} = \frac{\sigma}{R} A \quad (13)$$

in which A with sufficient accuracy may be represented by the cross-section. The ideal processing program is illustrated in Figure 9, in which the deforming force is modulated so as to equal the total resisting force ($F_{ST} - F_p$) when the desired end shape has been attained.

Forming of liquid metals by electromagnetic forces requires only moderate fields intensity, since their high electrical conductivity is little affected by temperature.

Liquid forming, however, is also feasible for high-temperature nonmetallics such as oxides, even though they are considered as nonconductors. As evidenced in Figure 10, their conductivity increases rapidly with temperature and at liquid temperature approaches the electrical properties of metals.

For the contact-free transformation of a liquid sphere into a nonspherical body of rotation by spinning, the spinning rate $\omega$ for the achievement of a specific distortion $\delta$ from the spherical shape is represented by the relationship

$$\omega = \frac{\left[8\left(\frac{\sigma}{\rho}\right)\delta\right]^{1/2}}{r^2} \quad (14)$$

in which r is the radius of the original sphere. The required spinning rates are relatively low. For example, for transforming a liquid aluminum sphere of 20 cm diameter into an oblate ellipsoid of 30 cm maximum diameter, the required spinning rate is approximately 12 rpm (Ref. 6).

The merits of contact-free forming are not only the absence of material contamination and nucleation sites, but also high surface smoothness, due to the vibrationless nature of the process, and the homogeneity of the microstructure.

In view of the involved equipment and control requirements, initial applications will consist of preshaped ingots with moderate shape accuracy requirements. The experience gained in such experiments is expected to lead to a gradual refinement of methods and tooling, so that eventually end-products of high perfection, such as optical components, can be produced.

Since the related tooling represents modifications of position-control equipment, space experiments will have to await the development and checkout of basic electromagnetic and/or electrostatic tooling.

### 3. Thick-Wall Hollow Spheres

The next logical modification of the basic sphere is the thick-wall hollow sphere, which may be looked upon as a sphere containing a gas bubble. Production starts, therefore, with the deployment of a (full) sphere, in which a bubble is grown by injection of an appropriate pressurized gas. The size of the gas bubble at any point of the growing process is exactly determined by the curvature-pressure relationship (4), in which the radius is determined by the pressure differential between gas and surrounding liquid, whose pressure in turn is related to the outside diameter and the environmental pressure. As illustrated in Figure 11, the equilibrium condition at any point of the growing process is defined by three pressures and two diameters. The pressure differential between the bubble ($P_2$) and the environment ($p_0$) is represented by:

$$p_2 - p_0 = \frac{4\sigma}{D_1} + \frac{4\sigma}{D_2} \qquad (15)$$

The only constant value is the volume of the liquid material, which is premeasured accurately for a desired final wall thickness and outside diameter. The interrelation between all these values is quite complex and can only be expressed by an implicit relationship. For a hollow sphere grown in vacuum, the interrelation between the constant liquid volume, bubble pressure P, and external diameter D is

$$V = \frac{\pi}{6}\left[D^3 - \left(\frac{4\sigma\, D}{pD - 4\sigma}\right)^3\right] \qquad (16)$$

While the external and internal diameters can be controlled accurately, manufacturing uniform wall thickness or centering of the bubble presents a problem, primarily because the sensing of its position is quite difficult in opaque materials. The most straightforward method is a dual-nozzle system, illustrated in Figure 12, in which the distance of the sphere-deploying outer nozzle and the inner "blowing" nozzle is equal to the final wall thickness. The effectiveness of this design depends on the capability to maintain the centered bubble position during detachment.

The unique characteristics of hollow spheres produced under zero-g are their seamlessness and microstructural homogeneity, both unattainable in terrestrial fabrication. A number of attractive applications has been defined, such as pressure vessels or ball bearings (Buzzard, Ref. 1). Mechanical properties may be improved by fiber reinforcement (strength) and by induced fine-grain solidification (ductility), both based on the phenomenon of mixture stability.

Space experiments may be carried out concurrently with (full) spheres due to the high commonality in equipment and methods.

### 4. Thin-Wall Hollow Spheres

While thin-wall spheres can be produced in the same equipment, the principle of formation differs entirely from the thick-wall sphere. A thin-wall hollow sphere is generated from, and by expansion of, a liquid membrane, much like a soap bubble. It may therefore be considered as an endless membrane whose spherical shape is again determined by the interrelation of radius of curvature and internal pressure. Since the pressure is constant and there are no mechanical interferences, the resulting shape has to be precisely spherical. In contrast to the (full) sphere, we have here two interfaces or two surface-tension shells, which are maintained during the expansion by supply of molecules from the enclosed bulk liquid. The relationship (4) is therefore modified to

$$\Delta p = \frac{4\sigma}{r} \qquad (17)$$

The wall thickness obtained at a finite sphere diameter can be controlled by a precisely premeasured amount of original material. The problem of bubble centering or wall-thickness uniformity does not exist, due to the interaction between the free-energy profiles of the two surface regions, which causes the bulk liquid to shift from thicker to thinner wall sections. This continuous movement can be well observed in soap bubbles. The minimum attainable wall thickness is obtained at the point where all bulk material is absorbed in the interfaces, so that further expansion would cause fracture. This critical thickness is in the order of a few molecular spacings. Its accurate definition is one of the objectives of space experiments, since the effect cannot be reproduced under the gravity environment. From the viewpoint of science, it will provide the missing link in the theories of the nature of the liquid state and interfaces, presently all based on assumptions and "models," and therefore inconclusive.

For technological applications, experiments with thin-wall hollow spheres will serve two purposes: (1) the development of techniques for the formation of flat membranes, in which the spherical membrane is merely a convenient test sample, and (2) mass-production of hollow microspheres for assembly into composite materials for structural or chemical applications, in which the locked-in high pressures may be used to advantage.

### 5. Flat Membranes

The fundamental criteria of the spherical membrane apply equally to flat membranes. Differences are merely in the methods of production.

In terrestrial fabrication, the prime limitation is the necessity of a substrate, which in turn limits the minimum wall thickness due to the difficulties in the liftoff process. In the gravity-free environment, tooling contact is confined to the edges, while the membrane itself is drawn free. While the interaction of bulk liquid and interface is identical to the spherical membrane, the expansion is produced by mechanical forces, introduced at the edges, rather than by pressurization.

A number of methods for the formation of membranes has been proposed. One, which can be carried out in a sphere-production chamber without significant additional tooling, consists of three operations illustrated in Figure 13: (a) blowing of a membrane-sphere to desired wall thickness, (b) deposition on a frame of the desired membrane-edge configuration, and (c) removal of the unused section of the sphere by "blowing up". The membrane remaining at the frame is under a homogeneous pressure environment and, consequently, essentially flat. Backflow of material from the sphere after blowup can be prevented by proper wetting characteristics of the frame.

Another method is pure mechanical drawing with continuous material supply, as illustrated in Figure 14. This method may be worked into a continuous process, in which the material is supplied from one side only and the membrane gradually solidified in approaching a revolving drawing drum, followed by a takeup drum (Ref. 5).

Membranes have a considerable applications potential in electronics, chemistry, and for advanced structural materials (laminated materials). The properties can be varied in accordance with specific application requirements. Fibers or whiskers may be added, which orient themselves during the drawing process, for strength increase and assembly into ultra-high-strength laminates. By appropriate solidification control, unidirectional orientation of the microstructure may be obtained. Heterogeneous membranes or laminates of extremely thin membranes of dissimilar materials may have semipermeable characteristics of interest in the processing of chemicals, such as sea water conversion. Thin membranes of electronic materials, presently deposited as films on substrates, may exhibit unique properties and a high degree of perfection due to the contact-free production.

Many of the applications can be pre-evaluated with spherical membranes, providing the data and experience for design of more sophisticated methods and tools.

## 6. Foams and Cellular Materials

The potential of producing materials of extremely low density has already been introduced in the form of an assembly of hollow microspheres. The same result may be achieved much more elegantly by foaming. In a zero-g environment foams are absolutely stable, since the liquid bulk remains in position between the surfaces of each foam cell wall, supplying new molecules to the interfaces during the process of expansion.

The two basic methods for the foaming of liquids are: (1) pressurization with extrinsically supplied gases and (2) intrinsic gas evolution from the liquid material.

The first method may be carried out in many ways, such as stirring or beating, where the gas is trapped in the liquid in an uncontrolled fashion, leading to a nonhomogeneous foam; or by gas injection in which the amount of gas deployed at each point and the distribution can be controlled with high accuracy. The obtained cell size is determined by the pressure and amount of injected gas and the resulting equilibrium between bubble pressure and bubble. At a coarse distribution, the foam represents a liquid continuum with dispersed gas bubbles. As the dispersion of individual bubbles is increased, the foam approaches a cellular configuration, consisting of flat cell walls which intersect at discreet points with high regularity; all surplus liquid material is concentrated in these four-wall intersect points. The flatness of the cell walls is determined by the pressure difference between adjacent cells. The mean internal gas pressure of the foam can be defined as the pressure of a hollow sphere whose diameter is equal to the average cell size. At fine cell size, this pressure is quite high and is in micron-size foam in the order of several thousand psi, depending on the surface tension of the material (Ref. 5).

The second, more elegant method is the bubble and cell formation by a combination of three phenomena: (1) outgassing due to depressurization at constant temperature, (2) bubble formation at preferred nucleation points, and (3) low-g mixture stability.

The process, illustrated in Figure 15, may best be described by means of an example: Fine particles are dispersed in liquid magnesium. The mixture occupies only a small section of a container in which it is held at 1 ata and 1,250°F, substantially under the boiling point of magnesium of 2,050°F at this pressure. The container is then vented to space vacuum of $10^{-7}$mm Hg, at which pressure the boiling point is approximately 400°F. Boiling sets in immediately at each particle; the particles act as nucleation sites for individual bubbles and a foam forms rather evenly, associated with an expansion of the material. As soon as the container is completely filled, it is locked and cooled through solidification. Due to the forced constant volume, the foam cannot collapse. This "nucleate foaming" may be carried out in more sophisticated ways and the foam may be in the form of an ingot or in end-product shape.

Although the low density materials obtained in this way exhibit high stiffness, particularly at high internal pressures, their strength, determined by the total cross-section of solid material, is moderate. This can be offset by the production of composite foams. In the formation of the cell walls, the liquid flow and the surface pressure will orient fibers or whiskers in the wall plane. The resulting material will have a combination of stiffness, strength and density, which exceeds present capabilities by almost an order of magnitude.

Plain foams or cellular materials have numerous applications simply as low-density materials. Whisker-reinforced foams provide unique core materials for high stiffness and strength-critical components, such as aerodynamic lift surface panels. Pressurized foams may be used effectively in deep-sea applications.

Finally it may not be out of order to take one look at nature which, after millions of years of development, uses the cellular structure very effectively, as in the case of wood, still our most versatile structural material. It has never been wrong to follow the advice of nature, and cellular materials may have potentials which we have not as yet realized.

## 7. Composite Casting

The most obvious application of low-g mixture stability is the production of composites from a mixture of a liquid matrix and solid reinforcements (Wechsler and Steurer, Ref. 2). It applies primarily to metal-matrix-whisker composites for the following reasons.

Casting of metal-base composites is unfeasible under terrestrial conditions, since the low viscosity of metals leads to immediate segregation.

Whiskers do not lend themselves to composite fabrication in the solid state, since they are incompatible with the high pressures required for effective diffusion-bonding of the metallic components (particles and foils). Furthermore, solid-state techniques are limited to low whisker content. For these reasons whiskers, in spite of their unparalleled strength in the order of millions of psi, have never been applied in metal composites. The casting of whisker composites in a low-g environment offers the following advantages.

High packing density, with consequent high strengthening and stiffening effect.

Random orientation, i.e., anisotropic mechanical properties. No product-shape limitations.

Preservation of whisker integrity, with consequently full effectiveness.

Production of complex high-performance components in one single operation.

Three types of whisker-composite castings are illustrated in Figure 16. In the basic type (Figure 16a) the randomly oriented whiskers cut across the relatively large grains of a common cast microstructure. The ductility of the metal matrix may be improved by the addition of finely dispersed particles, which act as nucleation sites during solidification, resulting in a fine-grain cast structure (Figure 16b). A material of high strength-to-density ratio is obtained by gas injection during mixing or at the entrance to the mold, producing a semifoamed matrix (Figure 16c). In contrast to the fiber-reinforced foam, the semifoamed matrix still represents a continuum.

The expected capabilities of whisker-composite castings in terms of strength/weight are illustrated in Figure 17 for two typical material combinations. In the calculation of data, allowance for uncertainties has been made by the use of a composite effectiveness factor of 0.5, which should assure reasonable reliability. The figure demonstrates that even at lower whisker content, the capabilities of cast composites substantially surpass any present high-strength structural alloy.

Composite casting is a typical mold process which may be carried out in two ways. (1) The two materials are precast in a mold on earth and remelted, mixed, and solidified in space; this process may be used for initial experiments. (2) Complete manufactur[illegible]ne in space in a special facility consistin[illegible] chamber, a feeding and mixing system, and [illegible]le molds.

In large-scale production, extr[illegible]icular operation of the facility is preferable due to the high amounts of heat involved and the advantage of cooling by radiation into deep space.

The primary applications of metal-base composite castings are to all types of high-performance structural components presently produced by forging and machining. In addition to their superior capabilities, space-produced composite components also show cost advantages in spite of the high cost of transportation to and from orbit. The average cost of forged and machined steel and titanium components is $200 per pound. This figure can be matched with use of expendable launch vehicles. With the availability of fully reusable vehicles, the cost of space-produced components drops to $110 per pound, including vehicle writeoff and indirect operations cost (Steurer, Ref. 1).

## 8. Dispersed Particle Castings

The processes employing dispersed microparticles are based on the phenomenon of liquid-solid mixture stability and are carried out exclusively by casting in or into a mold. For submicron size particles, random distribution is maintained even in a gravity environment due to Brownian motion. The particles required for the proposed casting processes are of micron size or larger, and segregation can only be prevented by a low-g environment. Three processes or products have been defined:

1. Castings with extremely fine grain size and the associated improved mechanical properties (strength and ductility).
2. Dispersion-strengthened castings.
3. Combination of 1 and 2.

In the fine-grain casting process, the particles act as seeds for nucleation and crystallization during solidification. The grain size can therefore be controlled by the degree of dispersion or the mean particle spacing. By sufficiently high dispersion, the resulting microstructure may be comparable to mill products, so that structural components of mill product quality can be obtained in one operation directly from the melt, bypassing the numerous operational steps of conventional fabrication, such as material refinement, forming and/or machining of component elements, and assembly into a final component by various joining methods. The one-step fabrication not only offers perfect anisotropy of mechanical properties and lower cost, but also increases reliability due to the substantial reduction of the number of processing variables.

The effect of dispersed particles, such as oxides, for the strengthening or rather the stabilization of strengthened microstructures of metals is well established. There are two methods of particle dispersion: (1) precipitation from solution at a discreet temperature and (2) mixing. In the gravity environment, the problem of mixture segregation confines both methods to the solid state, such as powder metallurgy techniques. The low-g environment permits the production of dispersion-stabilized alloys from the melt, either in the form of ingots for secondary terrestrial processing, or in the form of end-shape components (Mondolfo, Ref. 2).

The product may further be improved by the combination of both applications, i.e., the simultaneous dispersion of two dissimilar particle types and sizes, resulting in a fine-grain dispersion-strengthened casting of high and well controllable mechanical properties.

As typical mold processes, experiments may be carried out in the same manner and with the same equipment described in the foregoing section for composite castings. The primary applications are structural materials, in the form of finished components or in the form of mill shapes fabricated on earth from space-produced ingots.

9. Supersaturated Alloys

Liquid-liquid stability finds primary application in the alloying of metals of high difference in density which are eighter immiscible or exhibit a miscibility gap in a certain composition range. The resulting multiphase metal is not an alloy in the common sense, but rather a mixture of alloyed material with another single phase. In a coarse distribution, it may be regarded as a metal/metal composite. Unique characteristics of such composite metals may be achieved by directional solidification, induced by a controlled thermal gradient, and the resulting material may have a fibrous structure with the associated directionality of properties.

By appropriate metallurgical and mixing techniques, the distribution of the discreet phase may be refined to a degree, where a "homogenized" system is obtained, referred to here as "supersaturated alloy" (Reger, Ref. 2). The primary application of supersaturated alloys is in the semiconductor field.

10. Thermosetting Alloys

The phase diagrams of metallic systems contain an abundance of intermetallics which are either formed during solidification from the melt or during solid-state cooling due to the varying solubility of component elements. For systems in which one element has a low melting point, such intermetallics may be formed from a mixture of the liquidized low melting element with solid particles of the other constituents. While the processing temperature is near the low melting temperature of the liquid phase, the resulting solid intermetallic is stable to its much higher melting temperature, as defined by the phase diagram. This principle has been applied for half a century in the dental restoration field where an intermetallic known as amalgam is formed from a mixture of solid silver and liquid mercury at room temperature. Since we deal with a liquid-solid mixture, the mixture stability of low-g offers the potential for producing high-temperature-resistant intermetallic materials at moderate temperatures.

The process of formation of intermetallics is one of solution, in which the liquid acts as solute and the solid as solvent. The criteria for favorable liquid metals are therefore (1) low melting temperature and (2) high solubility in other metals.

Requirement (2) excludes sodium, potassium, and lead, as their solubility is low in all metals of technical usefulness. Promising candidates and their melting points are:

| Metal | Melting Temp. (°F) |
|---|---|
| Mercury | -37 |
| Gallium | 84 |
| Lithium | 356 |
| Tin | 450 |

The process of complete solution may be enhanced, and the setting time reduced, by "curing" at elevated temperature. The intermetallics so produced have therefore been designated as thermosetting alloys.

A considerable number of candidate compositions has been defined from phase diagrams and solubility calculations. As an example, the composition and expected temperature stability of gallium-base thermosetting alloys are listed in Table 2. All these alloys can conveniently be prepared at room temperature in view of the undercooling capability of gallium. Laboratory experiments to determine optimum setting temperatures are in progress.

The low working temperature together with the initially liquid condition further permits the addition of strengthening fibers which are incompatible with the high melting temperatures of conventional alloy production.

The process is extremely sensitive to mixture distribution homogeneity, attainable only in a gravitation-free environment. Initial space experiments can be carried out without any particular facilities. Eventually, it may be possible to produce intermetallic components in one operation with almost negligible heating requirements.

It is too early to assess the full potential of the concept of thermosetting alloys. Its prime attractiveness is the fact that it represents the first departure from the alloying methods practiced since the bronze age, all based on the complete melting of all constituents.

## 11. Containerless Melting of High-Temperature Alloys

The alloying of metals with extremely high melting temperatures encounters extreme difficulties and limitations in terrestrial production due to reaction with, and contamination by, the necessary crucible. These shortcomings are completely eliminated by containerless melting in a low-gravity environment. A preshaped ingot, compressed on earth from granules of the component elements, is deployed in a position control system, which at the same time may serve for induction heating (Frost, Ref. 2). After melting, it assumes spherical shape, and the various processing methods for liquid spheres may be employed, such as reduced convection for gas removal and mixture homogeneity. Solidification cooling is achieved by radiation to the cooled chamber wall.

Since the product is merely an ingot, it has not particular shape accuracy requirements. However, considerable problems are encountered in the tooling for the involved extreme temperatures. For this reason, experiments should be deferred until tooling experience has been accrued in experiments at lower temperatures.

The applications of refractory metal alloys are well known. Once production status has been achieved, ingots may be produced in shapes more adaptable to terrestrial secondary fabrication by means of contact-free liquid forming techniques (process 2).

## 12. Growing of Single Crystals

The primary criteria for the formation of a single crystal are of a metallurgical nature and have to be observed regardless of whether formation is carried out on earth or in space. Growing single crystals in space therefore introduces no new process, but rather an improvement of the conditions and controllability of existing processes, with the objective of improved products and new material types (Henry, Ref. 2). While at first glance this may appear not too exciting, one must realize that in the field of single crystals even marginal gains in capabilities may open up entirely new fields of application with considerable technological and commercial potential.

Single crystals are produced by three basic types of processes: growth from solution, growth from the melt, and growth from the vapor. For the reasons stated above, any description of the well established processes is omitted and the discussion confined to the gains which may be obtained in the low-g environment.

The most significant gain, common to all three methods, is derived from the absence of thermal convection. Since single-crystal formation is achieved by maintaining a steep thermal gradient at the solid-liquid interface, under terrestrial conditions it is necessarily associated with thermal currents, which are often extremely violent. Such motion induces irregularities in the crystal structure as well as dislocations in the atomic lattice. In some materials it even precludes the formation of a single crystal, as motion basically enhances nucleation, and consequently polycrystalline solidification.

Convection cannot be entirely eliminated in a zero-g environment, since there are other sources of convection. Of particular concern is the liquid motion induced by variable surface tension at the liquid-solid interface as well as at the environmental interface (surface) (Grodzka, Ref. 2). Such other types of convection, however, are of a substantially smaller magnitude than thermal convection, so that in zero- or low-g a considerable improvement of crystal perfection can be expected.

Another detriment in single-crystal growth is the material contamination induced by the container, whose presence is imperative under terrestrial conditions in all methods with the exception of a few growing techniques from the melt, such as the Czochralski method. For crystal growing from the vapor, a container is, or course, also required in space. However, solutions as well as molten metals under low-g conditions can be suspended free without any tooling contact by proper positioning or liquid management techniques.

In the growing process from a solution, low-g offers two additional advantages: (1) the stability of supersaturated mixtures, as discussed in process 9, and (2) the potential elimination of a mechanical support for the seed, which may introduce contamination as well as stresses in the crystal.

Presently, only the first two methods, growing from solution and from the melt, are considered for space experiments. One experiment, the growing of gallium arsenide single crystals from solution, is already in preparation for the first orbital workshop (Parks, Mazelsky, Kulshreshtha, Ref. 2).

13. Amorphous Materials (Glasses)

The capability of contact-free suspension of liquids in zero- or low-g and the minimized convection eliminate two powerful sources of nucleation, and consequently offer the potential of producing otherwise crystalline materials in the amorphous state (Olsen, Ref. 1).

While this permits supercooling of essentially all materials, the achievement of amorphous solidification of metals on a technically meaningful scale must be considered unfeasible, in view of their low viscosity and the required extremely high cooling rates, which can only be achieved by contact-cooling of thin layers.

In contrast, the viscosity of most liquid nonmetallic inorganics, such as oxides, is extremely high and differs from metals by approximately 10 orders of magnitude. Consequently, convection from any source is virtually eliminated in a low-g environment. Furthermore, the transition from the liquid to the solid state is much more gradual than in metals, extending over a wide range of viscosities and temperatures. Both these factors render them less susceptible to the intrinsic formation of nucleation sites and permit the suppression of crystal growth at comparatively low cooling rates, adaptable to noncontact (radiation) cooling. If we further eliminate external nucleation sites by contact-free suspension, the capability of producing nonmetallic inorganics as amorphous materials or "glasses" is virtually assured. Feability has further been verified in laboratory experiments, carried out by North American Rockwell under transient low-g conditions (Ref. 7).

In the envisioned in-space production, preshaped crystalline oxide ingots are deployed in an electrostatic positioning system. Several methods of contact-free heating to the involved high (3,000 - 4,500°F) temperatures have been proposed, such as (1) initial radiation heating with additional induction heating in the upper temperature regime of increasing conductivity, (2) arc-image furnace, (3) solar furnace, (4) dielectric heating. In the liquid state, an oxide-rich gas envelope will be required. Cooling is achieved exclusively by radiation to the cooled chamber wall. The employment of liquid forming techniques (process 2) may further permit manufacture of finished optical shapes with surface finishes not attainable in terrestrial grinding and polishing processes.

With the proper processing facilities, essentially all oxides can be produced as glasses. Such new glasses would exhibit optical properties not attainable in conventional silicate, borate, and phosphate glasses. The potential in advanced optical systems is apparent. Further, by the addition of transition metal oxides, semiconducting glasses can be obtained which could take the place of conventional semiconductors (Deeg and Happe, Ref. 2).

14. Unit Separation Process

For the separation and/or purification of species of minute difference in molecular weight in liquid suspension, such as microorganisms or isotopes, two methods are commonly used: (1) ultracentrifugal separation and (2) electrophoresis.

Since both methods are highly sensitive to convective currents, the minimized convection of the low-g environment is expected to significantly reduce, if not entirely remove, the capability limitations of terrestrial production. The primary gains are higher resolution and higher yield, as well as shorter processing time.

The fermentation process of micro-organisms, prior to separation, may likewise be enhanced by a low-g environment in the form of higher growth rate and density. This has been verified in biosatellite experiments (Jordan, Ref. 2).

The low temperatures and ultraviolet radiation available in space even though not unique may further be used to advantage for product preservation (freeze-drying) and sterilization (McCreight, Ref. 2).

The processes concerned are very delicate and require specialized equipment. However, even a moderate success of such space experiments would be justified by the high product value in dollars per pound and the contribution to human welfare.

Summary of Selected Processes and Products

A comprehensive summary of the 14 processes discussed above, which identifies primary processing characteristics and products, is presented in Table 3.

## DEMONSTRATION OF PROCESS CAPABILITIES IN SPACE EXPERIMENTS

If we detach ourselves for a moment from all the details of the effects of the low-g environment, and its applications, the net result of the foregoing discussion of individual processes is an impressive list of unique products and product capabilities which we could never achieve in the ever-present terrestrial gravity environment. The immediate question is, then, how and when can we turn these so-far conceptual capabilities into reality.

As far as the required sustained low-gravity environment is concerned, our advancements in space systems not only provide this environment but also the full capability to operate in this environment. Manned operations will be further enhanced as soon as the space shuttle becomes available.

The development of space manufacturing processes in terms of tooling and product hardware comprises the following.

1. Verification of the conceptually and theoretically predicted capabilities.
2. Refinement and optimization of methods, tooling, and products.
3. Scale-up of tooling and products with regard to size and production quantity.
4. Manufacturing of specific products for specific applications and checkout of such applications, as the first step toward utilization and commercial operations.

Although, on a laboratory scale, the verification of some effects and the development of some tooling details can be carried out in equal-density simulation and in free-fall tests on earth, the demonstration and optimization of the complete processes can only be accomplished under the sustained low-gravity environment of space experiments.

The term "experiment" has been generally accepted for in-space investigations in various disciplines, such as astronomy, radiation research, biochemistry, and others. It is therefore retained, even though space manufacturing "experiments" represent the development of an entirely new field of technology, from initial demonstration tests to a full-scale production capability.

The question how and when we can expect to achieve this capability may then be rephrased more accurately as (1) which experiments should be carried out first or what is the most effective experiment program, and (2) what are the required experiment facilities.

The definition of an effective experiment program is approached in four steps:

1. Assessment of relative processes effectiveness on the processes' own merits, regardless of facility requirements.
2. Time-phasing of processes on the basis of step 1, above, by the additional consideration of research and tooling development lead frames.
3. Assessment of facility requirement commonalities and definition of basic experiment facilities.
4. Integration of steps 1, 2, and 3 in an effective minimum-effort experiment program.

Assessment of Process Effectiveness

Even for new terrestrial processes, the assessment of effectiveness prior to hardware tests is quite complex and entails numerous intricate tradeoffs, whose numerical representation is difficult. For space processes, this task is necessarily more complex and more difficult in view of the complete absence of any precedent and the unconventional operational conditions. It would exceed the objective of this discussion to analyze the numerous fundamental, technological, and operational criteria, and their interrelation. Instead, they are combined in, and represented by, there major effectiveness criteria:

1. Functional Effectiveness, which may also be termed as probability of success. It includes uniqueness and soundness of the concept, various fundamental and technological process criteria as well as adaptability to space operations (vehicle constraints, environmental interferences, power and supply requirements, logistics, and astronaut participation).
2. Product Effectiveness, including capabilites in terms of uniqueness or degree of superiority over conventional capabilities, cost effectivenss, applications, and the total gains (pay-off) in such applications.
3. Growth Potential, in terms of process or product capabilities, adaptability to full-scale production or commercial operations, and potential modifications leading to new processes and products.

The relative rating of these three criteria for each of the previously discussed processes is presented in the first three columns of Table 4 in the form of three effectiveness levels (1 = lowest, 3 = highest). The resultant rating $R_p$ in fourth column represents the relative effectiveness of each process per se, without consideration of experiment development and hardware problems.

For the definition of experiment priorities, two additional criteria have to be taken into consideration: (1) the lead time for necessary fundamental and technological R&D and (2) commonalities in facility requirements. It is apparent that, as in any new development, each process requires a certain R&D effort. Therefore, in columns 5 and 6 an adjustment of the basic process rating is made only in those cases where the required R&D substantially exceeds the normally expected level in terms of effort or lead time. By the same token, a positive adjustment is made where the R&D in connection with one process will generate generally applicable experience.

The resulting adjusted rating $R_x$ in column 7 permits a preliminary timing of experiments, as indicated by process effectiveness or "desirability" and R&D lead times.

In the last three columns of Table 4 the experiments are grouped into three phases. A distinction is further made as to the experiment scope and objective:

1. Experiments of an exploratory or developmental nature with tentative methods and tooling (identified by a light circle).
2. Capability demonstration experiments in which a high assurance of success justifies tooling for a specific product (identified by a dark circle).

Experiment Facility Requirements

The identified phases could serve as an experiment program, if each experiment would be carried out in a separate facility. This is, however, impractical and unnecessary, as extensive commonalities in tooling requirements indicate the potential combination of several experiments into a limited number of multipurpose facilities.

A distinction of the primary facility requirements is determined by the following basic functional criteria.

1. The required mode of liquid material "suspension", either by contact-tooling (closed container, mold) or by means of a contact-free positioning and holding system.
2. The processing temperature regime, distinguishing between moderately high temperatures (3,000°F maximum) and extremely high temperatures (3,000°F - 5,000°F).
3. Special requirements, peculiar to one specific process only.

Commonalities between processes with regard to 1 and 2 above as well as specialized process requirements (3) are identified in Table 5. It is apparent that of the 14 identified processes, 11 can be carried out — assuming proper adaptability to secondary tooling for specific experiments — in three basic facilities:

a. Mold-type facility with moderately high temperature capability for the following processes.

   Foams and cellular materials (6)
   Composite casting (7)
   Dispersed particle castings (8)
   Supersaturated alloys (9)

b. Free-processing facility with moderately high temperature capability for the following processes.

   Production of spheres (1)
   Liquid forming (2)
   Thick-wall hollow spheres (3)
   Thin-wall hollow spheres (4)
   Flat membranes (5)
   Single-crystal growth from the melt (Czochralski method) (12)

c. Free-processing facility with extremely high temperature capability for the following processes.

   Containerless production of refractory metal alloys (11)
   Amorphous materials - glasses (13)
   Liquid forming of glasses (13 plus 2)

Of the remaining three processes, thermosetting alloys (10) and unit separation (14) require special facilities. The growing of single crystals (12) is either carried out in special facilities or in Chamber B, depending on the growing method.

DESCRIPTION OF TYPICAL EXPERIMENT FACILITIES

In view of the elementary nature of the initial experiments it will be expedient to start out with simplified versions of the three basic facilities or "experiment chambers." The gradual addition or exchange of subassemblies and specific tooling will lead to a continuous increase of capabilities and provide the design experience for the construction of larger and more complex chambers. The following discussion introduces, therefore, two versions for each basic facility: a simplified chamber (a, b, c) and high-capability chamber (A, B, C). Whether the high-capability chambers will necessitate a new design and construction or can be obtained by a gradual in-space modification of the original chambers will be determined by the experience gained in initial experiment operations.

Mold-Casting Chamber A — A conceptual design of the initial mold-casting chamber type a is shown in Figure 18. It consists basically of a resistance-heated and water-cooled mold assembly, a heat-shielding chamber with access and viewing ports, and a power and control unit. The material is supplied in a thin mold of standard configuration, which is simply inserted in the mold assembly for processing. The chamber has provisions for mold evacuation, if necessary. Optional mixing or foaming attachments are connected with the mold assembly by means of a multiple-attachment head located at the rear port. Another optional attachment is a material supply system, which permits the filling of a number of empty (vacuum-vented) molds from the same "heat".

The advanced and larger chamber A follows the same design concept, except for an integrated material supply system, with permanently installed mixing and gas injection units. The mold assembly is adaptable further to various mold-insert shapes. The entire chamber is centrally controlled.

Free-Processing Chamber B — Both chambers b and B for the free-processing of metals or metal-matrix composites are similar in design. Both require an integrated material supply system and a heat-radiating spherical chamber with adequate insulation to the shirt-sleeve environment. They differ primarily in size, total heat input, and in the sophistication of the free-suspension system.

A conceptual design of the smaller chamber b is shown in Figure 19. The three major subassemblies are the material supply system, the processing chamber, and the power supply with central controls.

The material supply system consists of the resistance- or induction-heated melting chamber, feeding system, permanently integrated mixing and shaking units, and a multiple attachment head for a variety of attachments in accordance with individual process and product requirements.

The spherical envelope of the processing chamber has to carry out three functions: (1) maintaining material temperature by means of radiant heating, (2) cooling the product through solidification by switching from a hot to a cooled inner wall, and (3) heat-protection of the shirt-sleeve environment by insulation and active cooling. Depending on the process and the type of experiment, any of the following heating methods may be used:

Melting in the material supply system, temperature-hold in the processing chamber by radiation (maximum temperature of 2,700°F).

Melting in the processing chamber by induction, temperature-hold by radiation (maximum temperature of 2,700°F).

Local melting (e.g., at nozzle) by resistance-heating and temperature-hold by radiation (small batches) (maximum temperature of 2,700°F).

Melting and temperature-hold by radiation (maximum temperature of 3,000°F).

The most important component of the processing chamber is the position-control subsystem. For the initial chamber b, a water-cooled two-coil system is proposed, whose effectiveness for positioning (holding in center) has been verified in laboratory experiments. An additional coil assembly for product rotation is exchangeable for optional use. Likewise optional is the use of separate induction heating coils, not shown in Figure 19.

The material deployment devices (nozzles and detachment mechanism) are attached at the multiple-attachment head. The chamber further provides for pressurization with appropriate gases and for space-vacuum "venting." The viewing and access port as well as the control panel are arranged on one side of the chamber.

The advanced chamber B (Figure 20) exhibits the same basic design, except for larger size and a six-coil position control system. The chamber is capable of the following functions.

Heating
Positioning
Rotating around one or two axes
Induced convection
Controlled deformation

The material supply system is omitted in this figure, since it is identical to the one shown in Figure 19.

Free-Processing Chamber C — In contrast or addition to chamber B, the free-processing chamber C requires the following capabilities.

1. No tooling contact during the entire processing cycle (solid-liquid-solid).
2. Processing of metallic and nonmetallic materials.
3. Temperature capability up to 4,500°F.

Requirement 1 excludes a material supply system, and the material is exclusively deployed in the center of the processing chamber in the form of a solid ingot. Since the chamber has to be adaptable to high-melting metals and nonmetals, it requires two interchangeable heating system. Metals may be heated by induction or electron beams. Nonmetals, such as oxides, may be heated by radiation or dielectric heating. The most effective radiation heating is the solar furnace. However, this furnace is excluded at this time in view of the extensive equipment and vehicle adaptation requirements. The other alternative of pure radiation heating is an arc-image system which, in view of vehicle constraints, appears only feasible for smaller material masses. For some nonmetals, the radiation heating requirements can be reduced by additional induction heating.

An attractive possibility of simultaneous heating and position control of nonmetals is an electrostatic system, illustrated in Figure 21. The material is heated by dielectric heating between six water-cooled plates. The position is controlled by alternate charging and discharging of the material with an electron and an ion beam, generating potentials between material and plates which cause the material to move.

Since oxides require an oxygen-rich gas envelope, it may also be considered to use the controlled movement of the hot gases for position control. Positioning with a gas flow is an early concept of space manufacturing.

In either method of heating, this chamber requires extensive cooling for the heating and position control elements, as well as for the chamber wall, which calls for an external heat exchanger (radiator).

Special Facilities — Special facilities or "experiment packages" consist of one or several self-contained units designed for a specific series of experiments. A typical example is the package for crystal growing from a supersaturated solution, as it is presently in preparation for integration in the first orbital workshop. A number of other experiment packages are described in Ref. 2.

DEFINITION OF A POTENTIAL EXPERIMENT PROGRAM

The development of an effective minimum-effort experiment program must integrate the following criteria (defined earlier).

1. Process and experiment effectiveness.
2. Optimum timing of experiment start.
3. Objective and scope of the experiments in each phase.
4. Required or available experiment facilities.

The first three criteria have been evaluated earlier and summarized in Table 4. This evaluation resulted in the arrangement of experiments in three phases and the definition of the experiment scope in each phase. The integration of experiment phases and scope with the proposed experiment facilities, are illustrated in Table 6. The resulting program provides for three experiment and facility phases as follows:

Phase I consists primarily in capability verification and demonstration experiments, including the related tooling development. It calls for the availability of the proposed chambers a, b, and c, and separate experiment packages, permitting performance of the following experiments.

1. Production of spheres of various sizes and from various metals. Refinement of deployment nozzles and detachment techniques. Checkout of position control systems.
2. Experimental production of thick-wall hollow spheres with emphasis on wall thickness uniformity control.
3. Various experiments on thin-wall metallic hollow spheres, with the primary objective of investigating the stability of membranes as related to thickness and material composition.
4. Checkout of various techniques for the production of foams and cellular materials. Investigation of foam stability and the potential of pressurized foams.
5. Casting of metal-matrix/whisker composites of various material combinations and reinforcement contents.
6. Exploratory formation of thermosetting alloys, varying composition, setting conditions, and mold shape.
7. Growing of single crystals from supersaturated solutions of various compositions. Investigation of process control requirements.
8. Production of small batches of glasses from various oxides. Investigation of solidification control parameters.
9. Exploratory unit-separation experiments by electrophoretic techniques. Investigation of attainable resolution and its dependency upon convection.

Phase II comprises the continuation of Phase I experiments with the objective of achieving full product and tooling capabilities, and the initial evaluation and demonstration of additional processes. Both are carried out in the new or improved chambers A, B, and C, and additional special experiment packages. The proposed Phase II experiment plan is as follows.

1. Improvement, modification and/or scale-up of processes and products initiated in Phase I.
2. Exploratory or initial capability development experiments on:

   Liquid forming
   Formation of flat membranes
   Production of fine-grain castings
   Production of dispersion-stabilized castings
   Containerless production of refractory metal alloys

Phase III represents the achievement of full capability in all processes. Some processes may even reach the initial production status, as indicated in Table 6. The facilities are not identified, as operations may either be carried out on the further improved or enlarged chambers A, B, and C, or in new semiproduction facilities whose construction may be motiviated by the increasing demand for specific products.

Merits of Extravehicular Operations

No mention has been made as to the location of the processing facility with regard to the vehicle, and it has been taken for granted that all operations are carried out inside in a shirt-sleeve environment. However, many experiments may be carried out more effectively by placing the chamber in an extravehicular position. While this may exceed the scope of the initial phases of the proposed program, it may well be introduced in Phase III. The advantages of extravehicular operations are:

1. No heat input into the vehicles
2. Effective chamber or product-cooling by direct radiation into space
3. Direct access to high vacua
4. Achievement of near-absolute zero-g

Extravehicular operations comprise two basic modes: "attached" and "detached." The attached mode provides more favorable heating and cooling conditions (1 and 2) as well as a more direct access to the ambient vacuum (3). An example for this type of operation is shown in Figure 22, which represents an extravehicular mold-casting experiment. By means of telescoping guide rails and an airlock system, the chamber is placed into the external position and operated by remote control. For radiation cooling, the mold heating assembly, consisting of two halves, is "swung away" from the mold, as illustrated in Figure 22.

A semidetached mode can be achieved by employment of a "serpentuator" (Ref. 9). Using the deployment device of Figure 22, the chamber is picked up from the guide rails by the serpentuator, whose complete three-dimensional maneuverability offers the following processing advantages.

1. Experiment positioning at a greater distance from the vehicle, further improving heating and cooling conditions.
2. Experiment positioning in the vacuum wake of the vehicle, where the vacuum surpasses the ambient vacuum by several orders of magnitude.
3. Experiment positioning in the centerline of the orbital path, where the g-level is near zero.
4. Combination of 2 and 3, above.
5. Control of the serpentuator movement by the free-drifting experiment material (chamber positioning system deactivated). This produces absolute zero-g at the mass center of the material.

The follow-mode (5), illustrated in Figure 23, combines the objective of the "free flying" detached mode with a simplified deployment and retrieval capability. It is only limited by experiment duration. If the duration and consequently the drift distance exceeds the operational range of the serpentuator, sustained zero-g can only be maintained in a fully detached, "free flying" experiment vehicle, whose attitude is likewise monitored by the drifting material. The deployment of such a vehicle exceeds the scope of the proposed experiment program, which is based on the orbital workshop, and has to await the establishment of a space station as a base for various modules. One conceptual design of the manufacturing module is shown in Figure 24. It consists of a larger working section, which remains attached to the station, and a detachable smaller section with the discussed free-flying capability.

This manufacturing module may be the first step toward independent space manufacturing vehicles or orbital factories operated by private enterprise.

## CONCLUSION

If I refer to orbital factories, it may well sound like calling on a distant future. However, if we scan in our mind what happened in not more than 12 years, from a small object sent into orbit, to men walking in space, to men setting foot on the moon, we have to admit that things occurred much faster than anyone would have dared to expect. Why, then, were space endeavors so extraordinarily successful? One of the reasons, of course, is a highly sophisticated state of technology. However, the prime reason is the simple fact that space is completely predictable and everything works with absolute precision, like the course of the planets. And any matter placed into space reacts with the same fully predictable precision to the basic laws of the universe. This is the very basis of manufacturing in space.

The predicatability of the behavior of matter in an environment completely free from any terrestrial constraints promises a high assurance of success. Once we have learned to match with our technology and tools the precision which space demands, we will get the same precision in return in the form of unique materials and products. The demonstration of this potential is the prime purpose of the proposed experiment program. And once this has been demonstrated, orbital factories will soon become a necessary part of modern technology.

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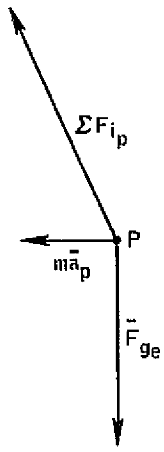


Figure 1. Definition of g.

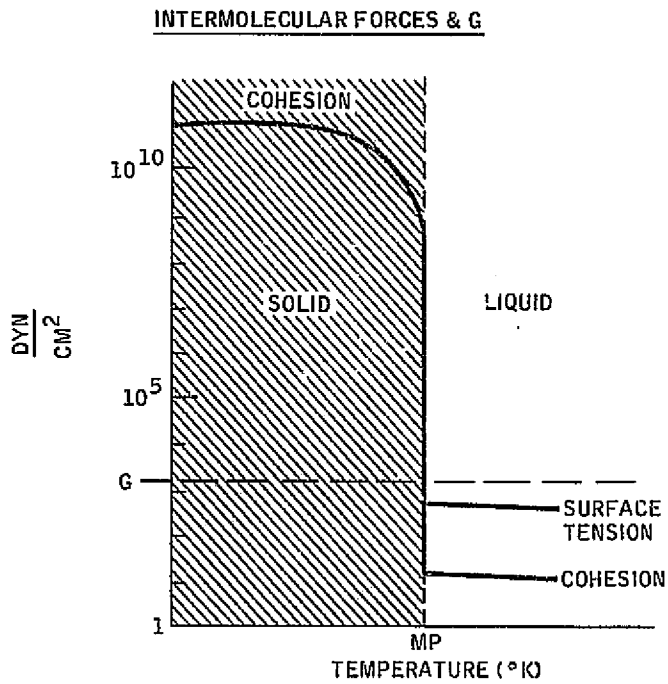


Figure 3. Intermolecular Forces anu g.

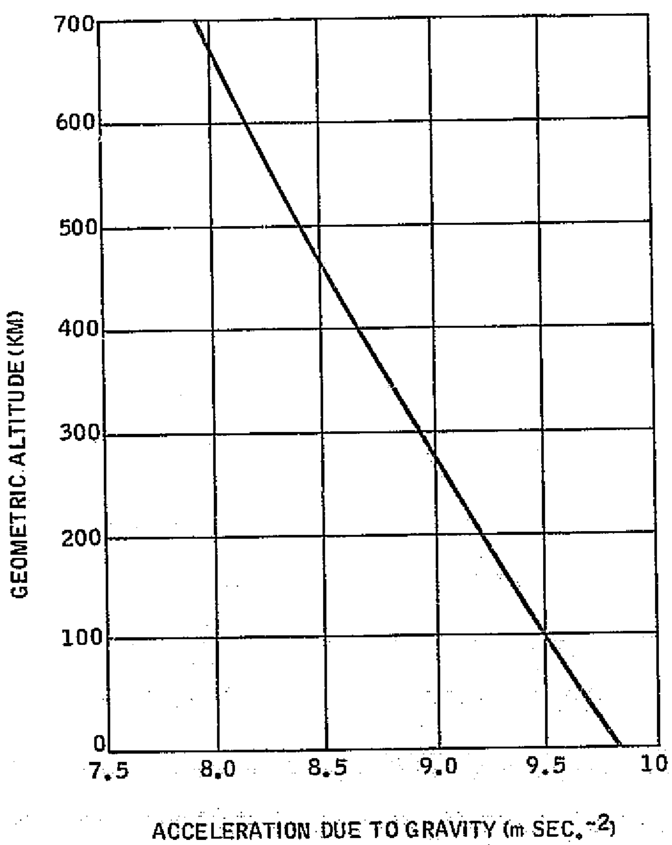


Figure 2. Acceleration Due to Gravity g as a Function of Geometric Altitude.

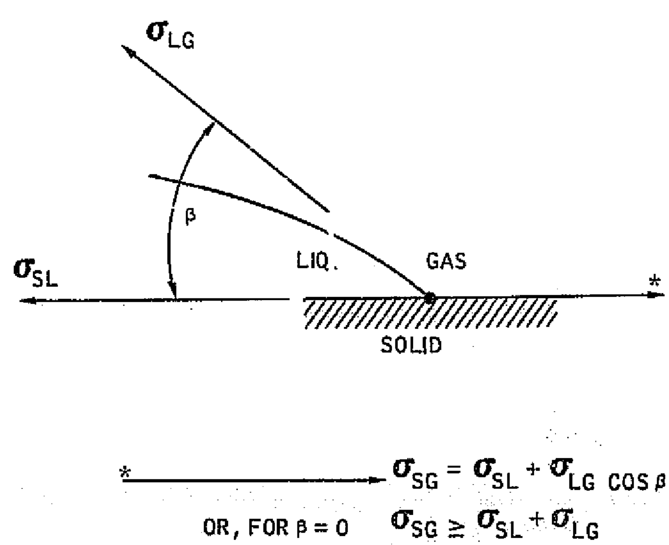


Figure 4. Surface Tension.

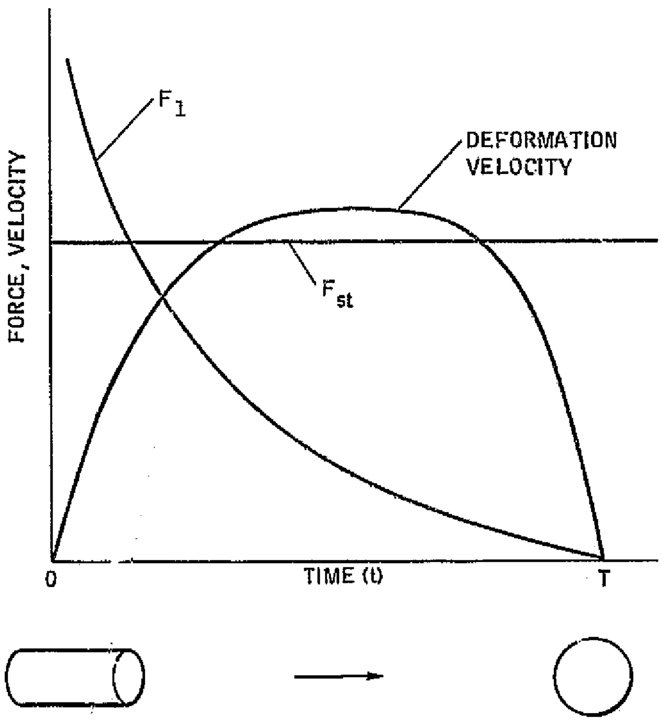


Figure 5. Variation of Forces and Deformation Velocity for Transformation of a Liquid into a Sphere.

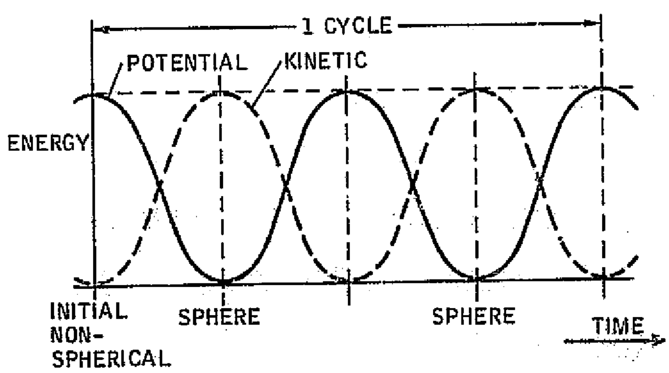


Figure 6. Sphere Oscillations in Terms of Potential and Kinetic Energy (Relationships 6 and 7 Represent the First One-Quarter Cycle).

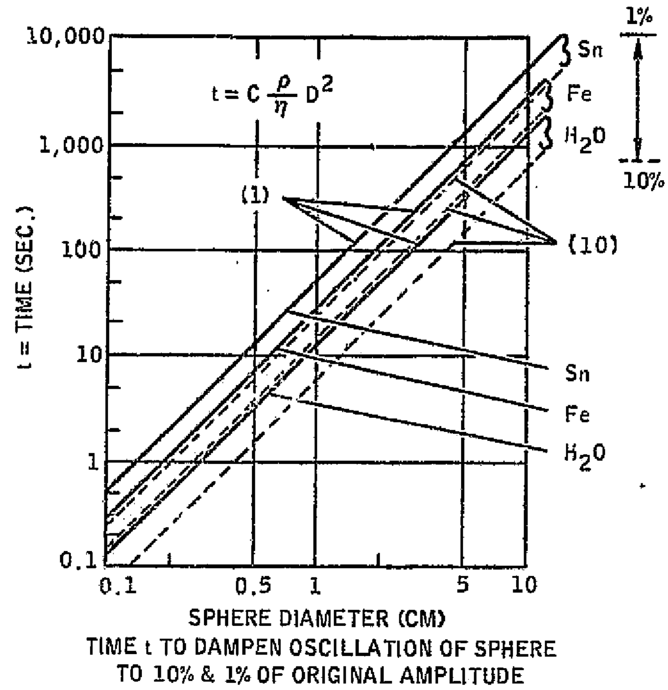


Figure 7. Dampening of Sphere Oscillations.

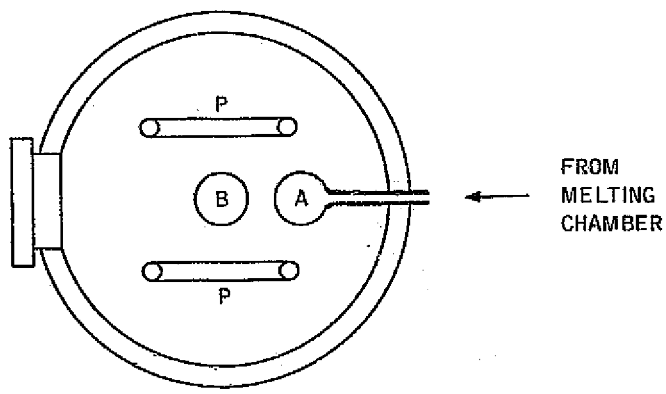


Figure 8. Processing of Liquid Spheres.

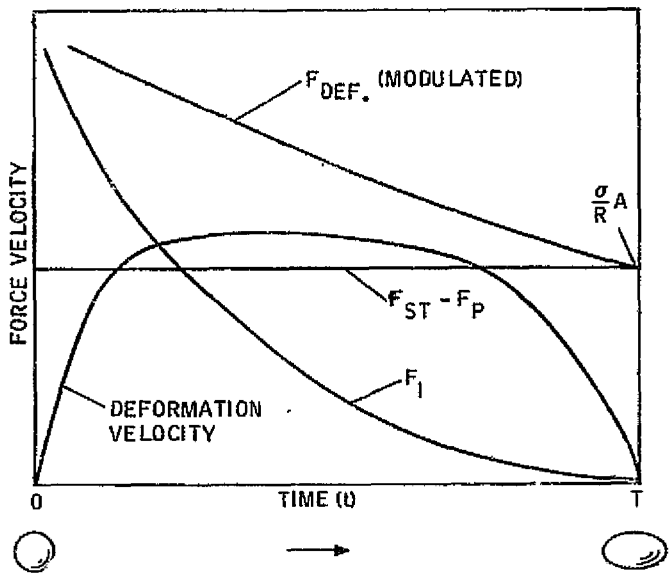


Figure 9. Variation of Forces in Contact-Free Liquid Forming (Modulated Forming Program).

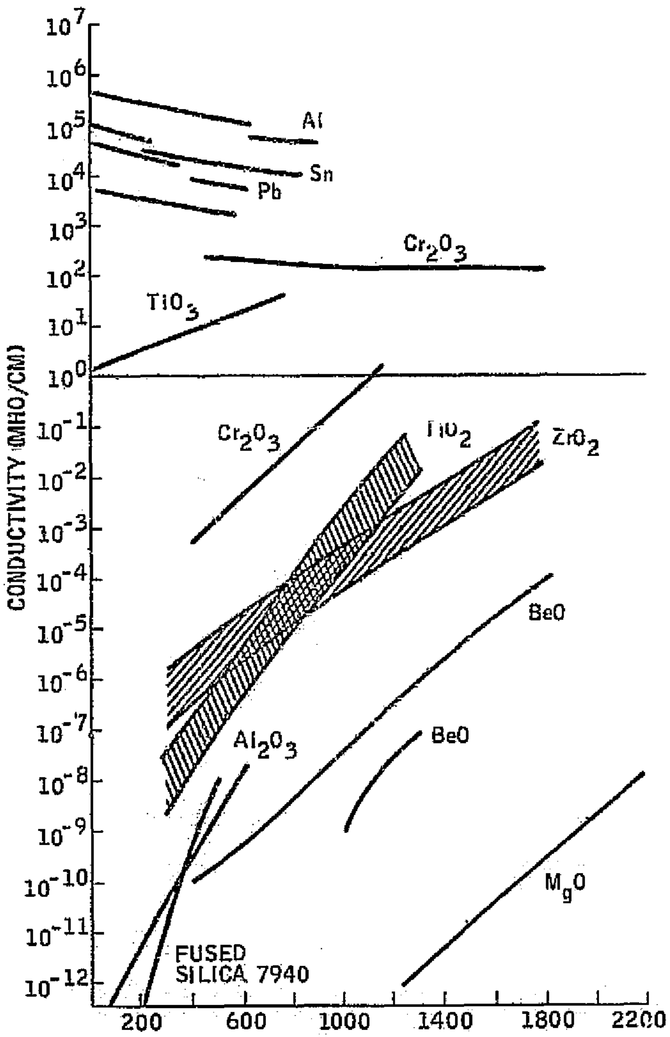


Figure 10. Electrical Conductivity of Material versus Temperature.

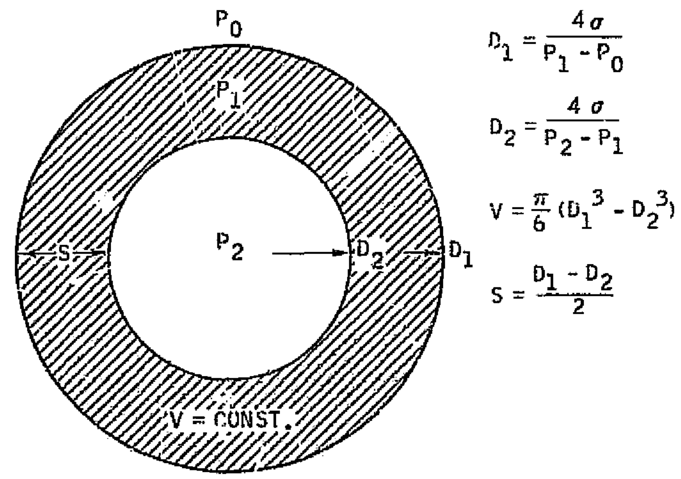


Figure 11. Pressures and Dimensional Characteristics of Thick-Wall Hollow Spheres.

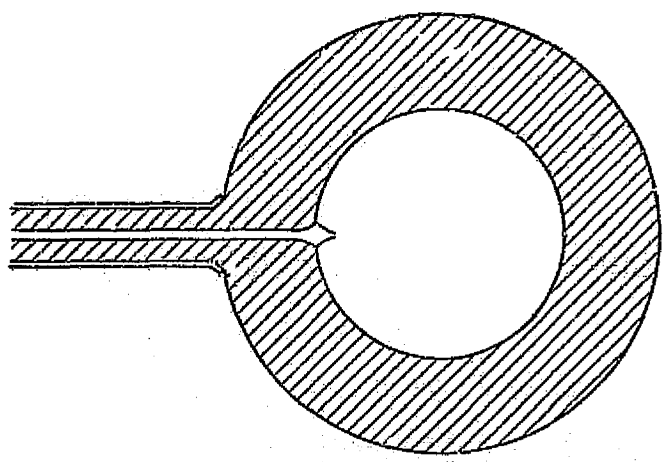

Figure 12. Dual-Nozzle Deployment System for Thick-Wall Hollow Spheres.

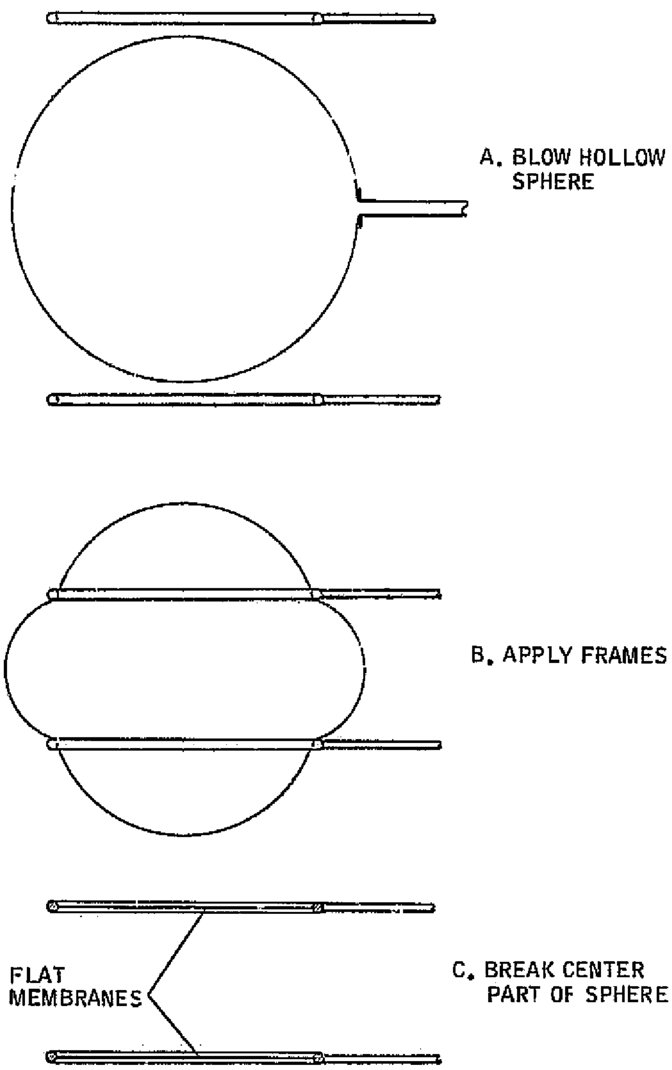


Figure 13. Formation of Flat Membranes from Hollow Spheres.

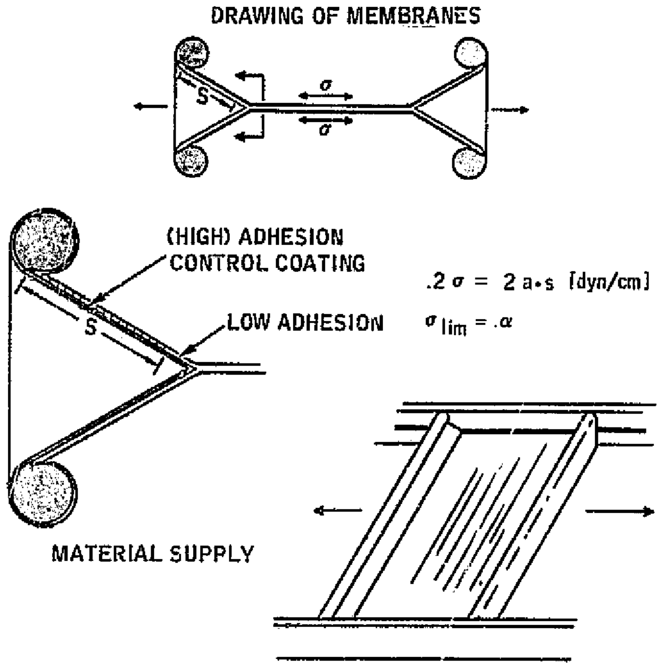


Figure 14. Drawing of Membranes.

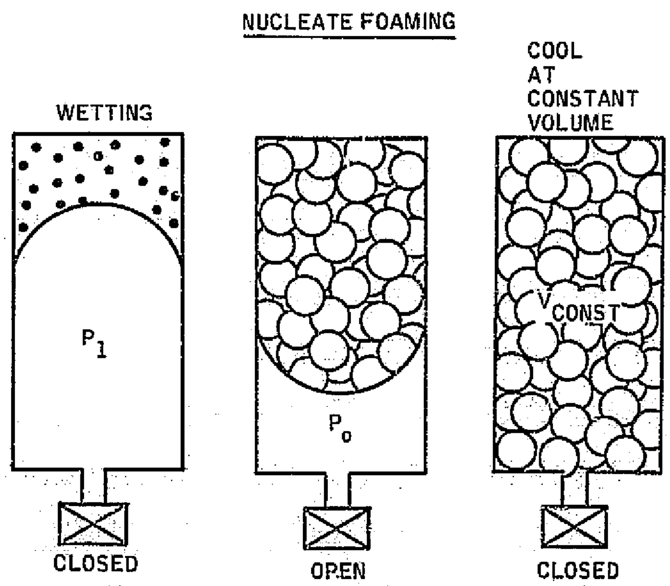


Figure 15. Nucleate Foaming.

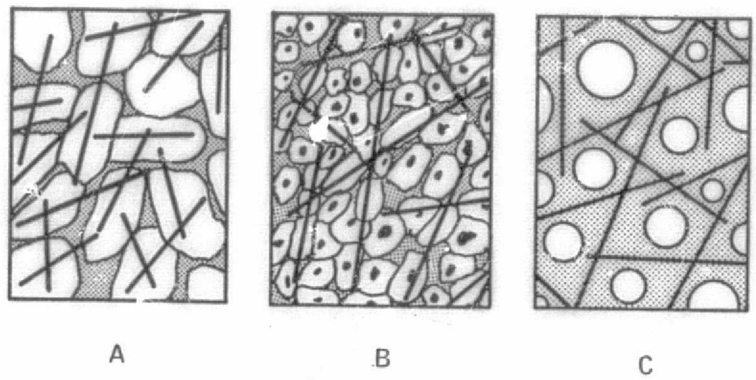


**Figure 16. Microstructures of Modified Cast Composites.**

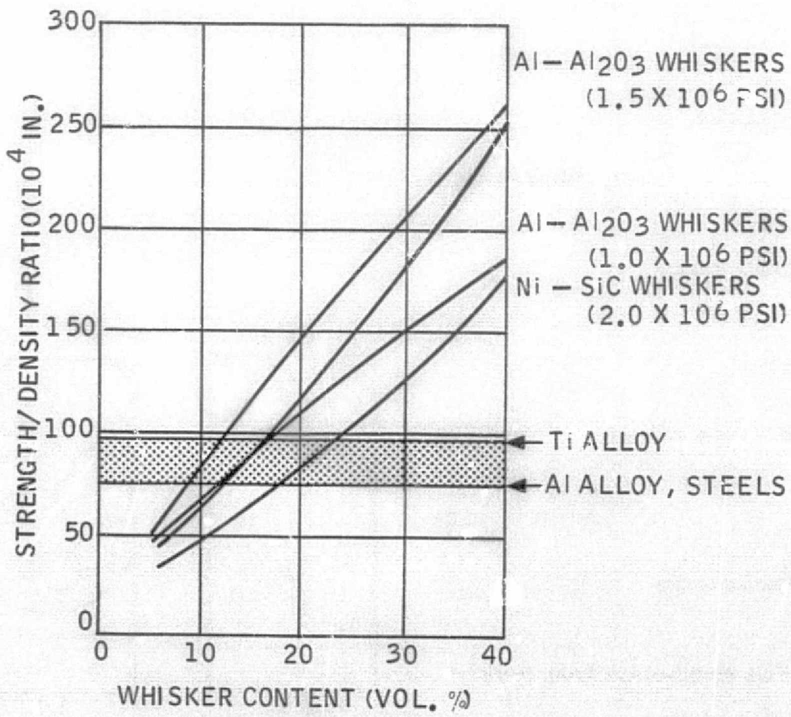


**Figure 17. Strength of Cast Composites in Comparison with Conventional Materials.**

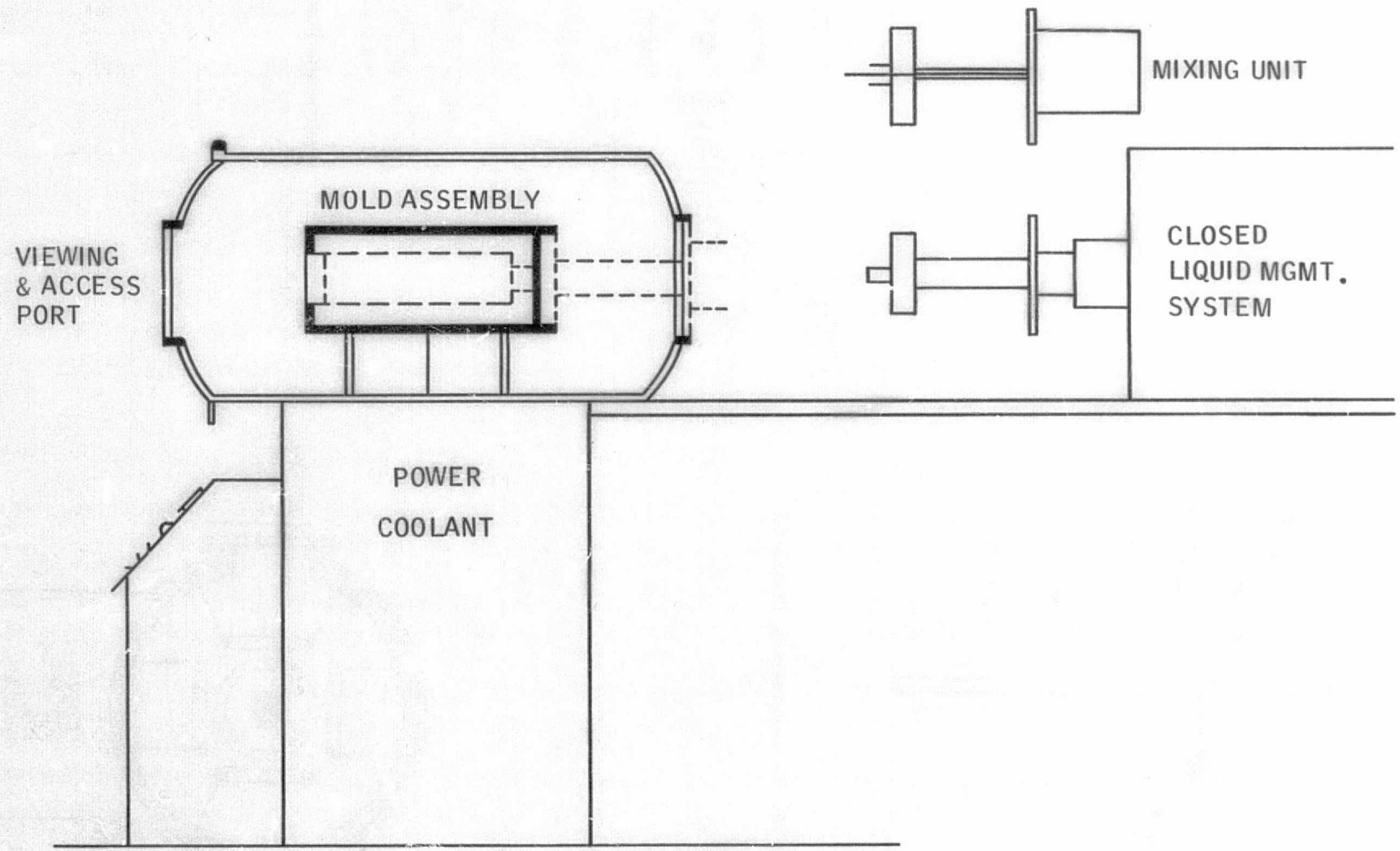


Figure 18. Mold-Casting Chamber b.

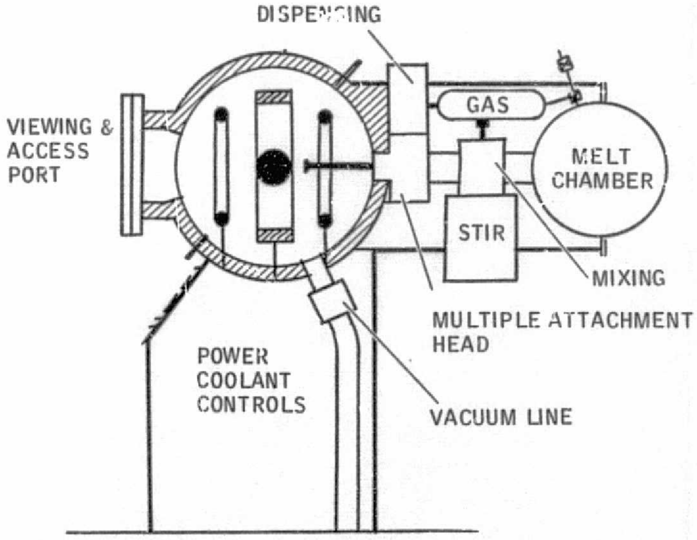


Figure 19. Free-Processing Chamber b.

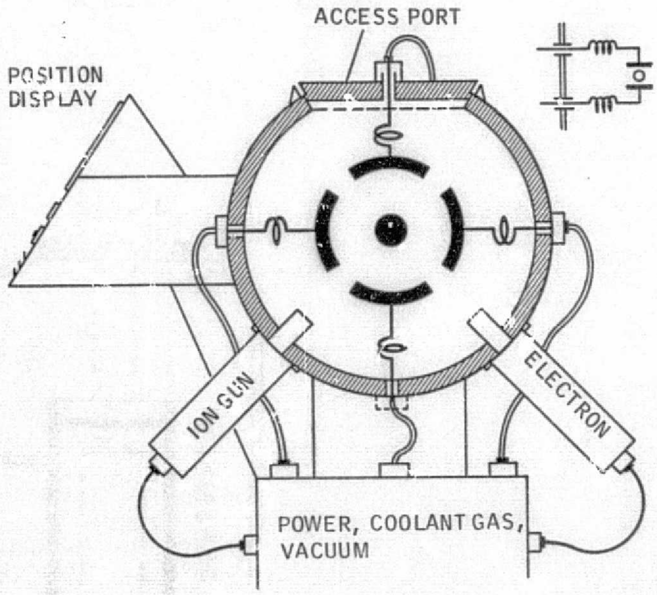


Figure 21. Electrostatic Positioning and Melting Chamber C.

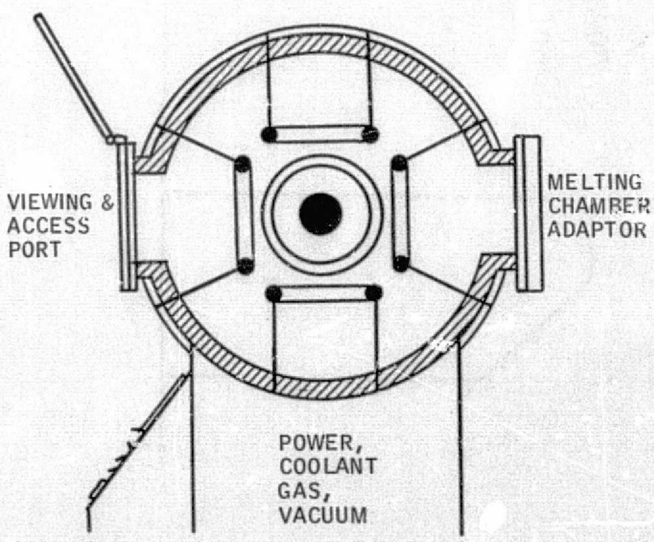


Figure 20. Free-Processing Chamber B.

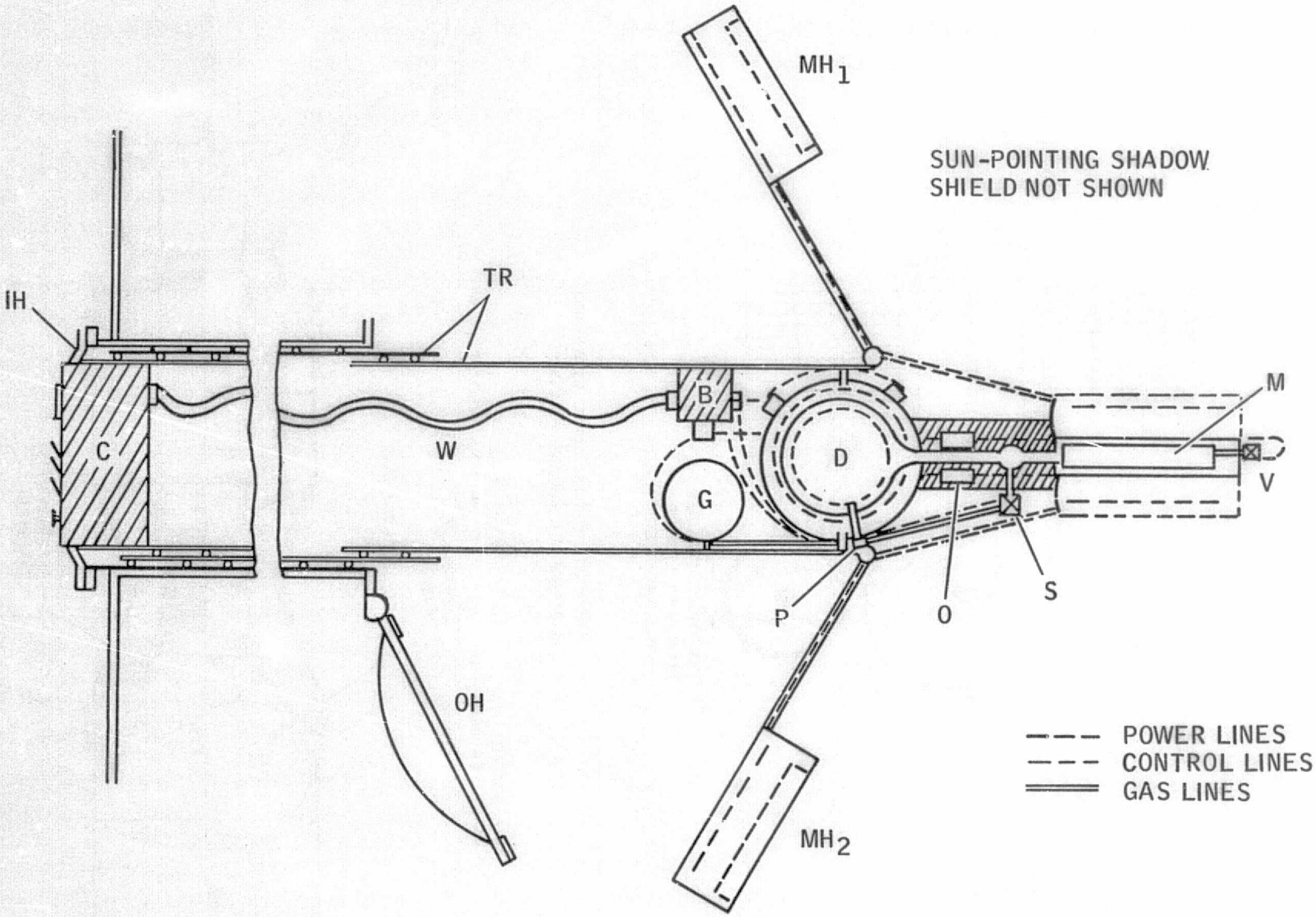


Figure 22. Attached Mode — Extravehicular Experiment.

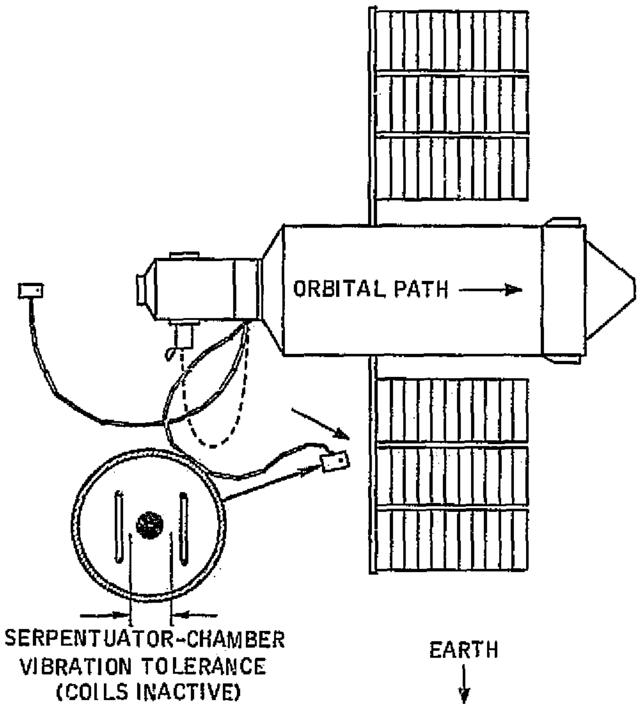


Figure 23. Extravehicular Operations
by Means of the Serpententuator.

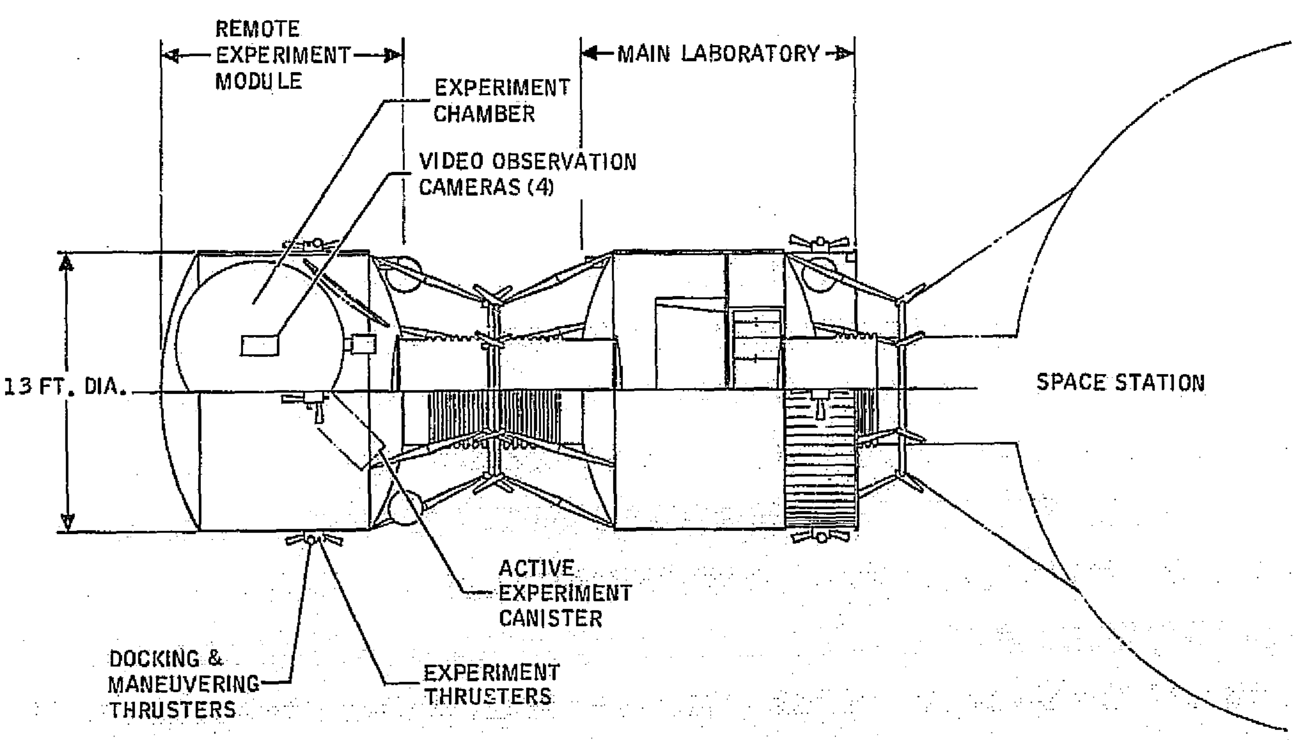


Figure 24. Space Manufacturing Module.

Table 1. Application of Zero-g Phenomena in Basic Processing Techniques.

| STATE | MEANS OF CONTROL | PRIMARY ZERO-G PHENOMENA | | |
|---|---|---|---|---|
| | | MIXTURE STABILITY | REDUCED CONVECTION | INTERMOL. FORCES |
| Liquid | None | Supersaturated Liquid/ Liquid Mixtures | | Contact-Free Formation of Spheres, Containerless Melting |
| | Induced Forces | Variable Density Mixtures | Unit Separation | Contact-Free Forming |
| | Mechanical Forces | | | Formation of Membranes |
| | Gas Injection | Liquid Continuum-Bubble Mixtures | | Formation of Hollow Spheres, Foaming |
| | Thermal Gradient | | Controlled Liquid/Motion | |
| | Solid Particles | Liquid-Matrix Composites | | Controlled Vaporization (Nucleate Foaming) |
| | Solid Interface | | | Adhesion/Deposition, Spreading |
| Liquid-Solid Interphase (Solidification) | None | Supersaturated Alloys Metal/Metal Composites | Reduced Nucleation | Containerless Solidification |
| | Thermal Gradient | | Single - Crystal Growth | Growth of High-Purity Single Crystals |
| | Solid Particles | Induced Nucleation Formation of Intermetallics | | |

Table 2. Candidate Compositions for Thermosetting Alloys — Gallium Base, Minimum Working Temperature of 80°F.

| LIQUID Ga (%) | ALLOYING ELEMENT (%) | INTERMETALLICS | TEMP. STABILITY (°F MAX.) | SOLIDIFICATION TIME (HR. AT RT) | TENTATIVE RATING |
|---|---|---|---|---|---|
| 46 | Mg 54 | $Mg_5Ga_2$ | 840 | | 1 |
| 56.4 | Al 43.6 | $Al_2Ga$ | 830 | | 1 |
| 34 (32.8) | Cu 66 | $Cu_9Ga_4$ | 1,650 | 4 | 1 |
| 13 | Ag 87 | | 1,100 | | 2 |
| 36.4 | Sb 63.6 | Sb Ga | | | 2 |
| 27 | Te 73 | $Ga_2Te_3$ | 1,450 | | 1 |
| 36 | Te 64 | Ga Te | 1,450 | | 1 |
| 18 | Au 82 | $Au_3Ga$ (+Au) | 840 | 5 | 1 |
| 22-27 | Au 73-78 | $Au_3Ga$ | 790 | | 1 |
| 34 (28-40) | Au 66 | $AuGa_2$ + AuGa | 900(+) | 8 | 2 |
| 91 | Li 9 | Ga Li | (low) | | 3 |
| 32 | 44Cu-24Sn | | 1,200 | 24 | 1 |
| 32 | 50Cu-18Sn | | 1,290 | 24 | 1 |
| 33 | 44Cu-33Au | | 1,200 | 8 | 2 |

Table 3. Summary of Major Process Characteristics.

| PROCESS DESIGNATION | LOW-G EFFECTS | PROCESS | PRODUCTS |
|---|---|---|---|
| 1 Production of Spheres | Undisturbed effectiveness of intermolecular forces | Formation by surface tension after deployment from nozzle or melting of ingots | Monolithic or reinforced spheres as high-precision end products or as ingots |
| 2 Liquid Forming | Undisturbed effectiveness of intermolecular forces | Form control by induced contact-free forces | Homogenous shapes of high accuracy & surface finish |
| 3 Thick-Wall Hollow Spheres | Undisturbed effectiveness of intermolecular forces | Simultaneous growing of sphere & centered gas bubble | Seamless hollow spheres from monolithic or composite materials |
| 4 Thin-Wall Hollow Spheres | Undisturbed interaction of interface energies | Formation at nozzle by pressurization (blowing) | Membrane-wall hollow spheres primarily for research |
| 5 Flat Membranes | Undisturbed interaction of interface energies | Conversion from thin-wall hollow sphere or by mechanical forces (drawing) | Ultra-thin, perfectly flat membranes from metals & nonmet. inorganics |
| 6 Foams & Cellular Materials | Undisturbed effectiveness of intermolecular forces; mixture stability | Bubble growth by gas injection or internal gas evolution | Low-density, high-stiffness structural materials; internally pressurized materials |
| 7 Composite Casting | Mixture stability | Mixing & mold-casting of liquids & solid reinforcements | Finished components of metal-matrix/whisker composites |
| 8 Dispersed Particle Castings | Mixture stability | Mixing & mold-casting of liquids & dispersed microparticles | Fine-grain metal castings; dispersion-strengthened alloys & components |
| 9 Supersaturated Alloys | Mixture stability | Mixing & casting of immiscible metals & supersaturated metal compositions | Metal-metal composites & new alloys |
| 10 Thermosetting Alloys | Mixture stability | Alloy formation at moderate temperature from liquid & solid elements | New intermetallic materials & composites |
| 11 Containerless Melting | Undisturbed effectiveness of intermolecular forces | Melting, purification & solidification without tooling contact | New & high-purity refractory metal alloys |
| 12 Single Crystals | Reduced convection; contact-free suspension | Conventional processes with improved crystallization. control growing from contact-free melt | Single crystals of high perfection, high purity & large size |
| 13 Amorphous Materials (Glasses) | Contact-free suspension; Reduced convection | Suppressed nucleation & crystal growth by contact-free melting & solidification | Glasses from various oxides with new optical properties; semiconductor materials |
| 14 Unit Separation | Reduced convection | Electrophoretic or ultracentrifugal separation with high resolution | New vaccines<br>Isotopes |

Table 4. Assessment of Relative Process Effectiveness.

| PROCESSES & PRODUCTS | BASIC EFFECTIVENESS* | | | | R&D* | | | PHASING* | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Proc. | Prod. | Pot. | $R_P$ | Fund. | Toolg. | $R_X$ | I | II | III |
| 1 Production of Spheres | 3 | 2 | 2 | 7 | | +1 | 8 | • | | |
| 2 Liquid Forming | 1 | 2 | 3 | 6 | | -2 | 4 | | o | • |
| 3 Thick-Wall Hollow Spheres | 2 | 3 | 3 | 8 | | -1 | 7 | • | | |
| 4 Thin-Wall Hollow Spheres | 3 | 2 | 2 | 7 | -1 | +1 | 7 | • | | |
| 5 Flat Membranes | 2 | 3 | 3 | 8 | -2 | -1 | 5 | | o | • |
| 6 Foams & Cellular Materials | 2 | 3 | 3 | 8 | | | 8 | • | | |
| 7 Composite Casting | 3 | 3 | 2 | 8 | | | 8 | • | | |
| 8 Dispersed Particle Castings | 3 | 2 | 1 | 6 | | | 6 | o | • | |
| 9 Supersaturated Alloys | 3 | 2 | 1 | 6 | | | 6 | o | • | |
| 10 Thermosetting Alloys | 2 | 1 | 3 | 6 | | | 6 | o | o | |
| 11 Containerless High-Temp. Melting | 3 | 2 | 1 | 6 | | -2 | 4 | | o | • |
| 12 Single Crystals | 2 | 3 | 3 | 8 | -1 | -1 | 6 | o | • | |
| 13 Amorphous Materials (Glasses) | 2 | 3 | 3 | 8 | | -2 | 6 | o | • | |
| 14 Unit Separation Processes | 1 | 3 | 3 | 7 | -1 | | 6 | o | • | |

*Explanation of Codes:
$R_P$ = process rating (1 = low rate)
$R_X$ = experiment rating
— = long lead time problems
\+ = beneficial tooling experience
o = capability development experiments
• = capability demonstration experiments

Table 5. Major Tooling Commonalities and Experiment Facilities.

| PROCESSES OR PRODUCTS | LIQUID SUSPENSION | | TEMP. CAPABILITY | | SPECIAL RQMT. | FACILITY REQUIREMENTS | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | MULTIPURPOSE | | | SPECIAL |
| | Mold | Free | 3000°F | 4500°F | | A | B | C | SP |
| 1 Production of Spheres | | X | X | | | | X | | |
| 2 Liquid Forming | | X | X | X | X | | X | X | |
| 3 Thick-Wall Hollow Spheres | | X | X | | | | X | | |
| 4 Thin-Wall Hollow Spheres | | X | X | | | | X | | |
| 5 Flat Membranes | | X | X | | X | | X | | |
| 6 Foams & Cellular Materials | X | | X | | | X | | | |
| 7 Composite Casting | X | | X | | | X | | | |
| 8 Dispersed Particle Castings | X | | X | | | X | | | |
| 9 Supersaturated Alloys | X | | X | | | X | | | |
| 10 Thermosetting Alloys | X | | X | | X | | | | X |
| 11 Containerless High-Temp. Melting | | X | | X | | | | X | |
| 12 Single Crystals | X | X | X | | X | | X | | X |
| 13 Amorphous Materials (Glasses) | | X | | X | | | | X | |
| 14 Unit Separation Processes | X | | X | | X | | | | X |

Table 6. Potential Experiment Program.

| PROCESSES OR PRODUCTS | EXPERIMENT PRIORITY | | PHASES & FACILITIES | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | I | | | II | | | | III |
| | o | • | a | b | sp | A | B | C | SP | |
| 1 Production of Spheres | | I | | • | | | • | | | ◉ |
| 2 Liquid Forming | II | III | | | | | o | o | | • |
| 3 Thick-Wall Hollow Spheres | | I | | o | | | • | | | ◉ |
| 4 Thin-Wall Hollow Spheres | | I | | • | | | • | | | • |
| 5 Flat Membranes | II | III | | | | | o | | | • |
| 6 Foams & Cellular Materials | | I | • | | | • | | | | ◉ |
| 7 Composite Casting | | I | o | | | • | | | | ◉ |
| 8 Dispersed Particle Castings | | II | | | | • | | | | ◉ |
| 9 Supersaturated Alloys | I | II | o | | | • | | | | ◉ |
| 10 Thermosetting Alloys | I | II | | | o | | | | • | • |
| 11 Containerless High-Temp. Melting | II | III | | | | | | o | | • |
| 12 Single Crystals | | I | | | o | | o | | • | ◉ |
| 13 Amorphous Materials (Glasses) | I | II | | | o | | | • | | ◉ |
| 14 Unit Separation Processes | I | II | | | o | | | | o | ◉ |

o Capability development experiments

• Process & product demonstration experiments

◉ Full-scale production experiments

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# CHEMICAL AND BIOCHEMICAL SPACE MANUFACTURING

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## OVERVIEW OF PROPOSED SPACE MANUFACTURING PRODUCTS

J. W. Gibbs, in the last decade of the 19th Century, was well aware that the gravitational environment has an effect on the way chemical reactions proceed on Earth. In his discussion of the celebrated Gibbs function, he devoted a full chapter to this question (see Literature 6). Subsequently this was forgotten and treated as a negligible influence, to surface again today in zero-g manufacturing.

In Figure 1, an overview is given of a new candidate products, considered for space manufacturing. They are the results of several years of conceptual studies by NASA and a broad cross-section of U. S. industry. A status summary of these proposals was given at the Space Processing and Manufacturing Symposium (see Literature 1) in October 1969. It shows a bewildering array of products and processes, using zero-g and vacuum as available in space flight, to produce new glasses, grow perfect crystals, make high strength filaments, create new light weight - high strength materials and finally produce chemical and biochemical products - better, faster and hopefully cheaper than we are able to do on Earth.

GLASSES
- STRESS-FREE BLANKS
- PHOTOTROPIC GLASSES
- CHRISTIANSEN FILTERS
- FOAM GLASS
- HIGH N GLASS
- IR TRANSMITTERS
- NEW GLASSES: $A\ell_2O_3$, $Zr_2O$, $Hf\,O_2$, $Ti\,O_2$

CRYSTALS
- ELECTRONIC/CERAMIC CRYSTALS
- PSN: $K_{0.5}Na_{0.5}NbO_3$
- Ga As, Ga Bi

FILAMENTS
- BARONS
- WHISKERS
- PLATELETS
- COMPOSITES

NEW MATERIALS
- $A\ell$ - $A\ell_2O_3$
- NICKEL THORIA
- SUPER CONDUCTORS: $Nb_3A\ell$, $Nb_3Ge$, $Nb_3Sn$
- SOLID LUBRICANTS: Pb-Cu; Pb-Fe
- DIRECTIONALS: Fe - FeS
- CERMETS
- AMALGAMS: Au, Ga, Pb COMPOUNDS

NEW PROCESSES
- SURFACE TENSION CASTING
- PARTICLE SUSPENSION
- CONTROLLED FOMAING

CHEMICAL PROCESSES
- FERMENTATION
- DIALYSIS
- LYOPHILIZATION
- DIFFUSION
- ELECTROPHORESIS
- CATALYSIS

METALLURGICAL PRODUCTS
- GAST COMPOSITES
- METAL FORMS
- PERFECT SPHERES
- SINTERS

SEED MATERIALS
- CRYSTAL SEEDS
- GLASS SEEDS

VACCINES

ENCYMES

ISOTOPES

ANTIBIOTICS

POLYMERS

TOTAL: 37 NEW POTENTIAL PRODUCE CLASSES

FIGURE 1 SPACE MANUFACTURING PRODUCT CLASSES

At first glance, the 37 potential new product classes in Figure 1 seem to be unrelated; however, it is the purpose of this paper, to show that there is a strong common reason for this selection. As a result of this common thread, it will be shown that the major payoff of space manufacturing will be found in chemical and biochemical areas noted in Figure 1.

For all proposed new processes, the essential portion of the processes will be in the liquid phase, the transitions of liquid to solid phases and in some cases (e.g., artifical diamonds) gaseous/liquid/solid transitions. The amazing array of new processes really treats variations of the liquid to solid phase transitions, such as melting/solidifying, condensation/evaporation and related processes such as bubble formation in boiling. These phase transitions are the realm of physical chemistry characterized thermodynamically by the Helmholtz and Gibbs functions which describe the rate of reactions possible, their stability and the energy necessary to make the reaction of process take place (see Literature 2, 3, 4 & 5).

## PHYSICAL CHEMISTRY OF ZERO-G

### Energy Criteria

Gravity, or the absence of gravity, has an influence on a chemical reaction, if the gravitational energy $E_g$ - is appreciable compared to chemical energy $E_c$. Consider a chemical reaction where these energies are equal.

$$E_g + E_c = E_g' + E_c'$$

In equilibrium, the transition rates $\vec{N}$ from left to right should be equal to $\overleftarrow{N}$ from right to left.

$$\vec{N} = \text{const}\ N(E_g)\ N(E_c) = \text{const}\ N(E_g')\ N(E_c') = \overleftarrow{N}$$

The only function, satisfying this equilibrium condition is the exponential

$$N(E) = N_o \exp\ (cE)$$

or the partition function

$$N(E_c) \quad N(E_g) = \exp \frac{E_c - E_g}{kT}$$

where k is Boltzmann's constant and T the absolute temperature. For gravitationally produced potential energy, $E_g$ = mgh one gets the barometric pressure formula

where m = particle mass
g = gravitational acceleration
h = height above reference plane

$$N(E_g) = N_o \exp(-mgh/kT)$$

Consider zero-g conditions (mgh is zero) $N(E_g)$ tends to $N_o$ and "levitation" sets in, an instability, which means independence of height h.

To have any effect at all, presence or absence of gravity has to be commensurate with the chemical energy $E_c$.

The gravity energy of one cc of water of height h = 1 cm is in c.g.s. units:

$$E_g/cc = mgh = 981 \text{ Dyne} \times 1 \text{ cm} = 981 \text{ erg}$$

In chemical reactions, we have the energy in mol-units; water has a molecular weight of 18 gr, thus

$$E_g/\text{mol} = 981 \times 18 = 1,8 \times 10^4 \text{ erg}$$

$$= 4,24 \times 10^4 \text{ cal}$$

Indeed, this energy is negligible to normal chemical heat of reaction, fusion etc., ranging from $10^3$ to $10^5$ cal/mol. However, long-term effects, such as diffusion, sedimentation, osmosis, electrophoresis and dialysis are energetically of this order.

Thus, we found, based on the energy criterium, two classes of processes, where zero-g has effects: mgh = 0

$$N(E_g) = 0; \frac{dN}{dh} = 0 \text{ levitation, instability and}$$

$$E_g \sim E_c \quad = \text{diffusion, sedimentation, osmosis}$$

Since calories are large energy units compared to those of interest, we prefer to calculate in ergs (1 cal = $4.185 \times 10^7$ erg). We look for processes with $E_c$ equal to $10^1$ to $10^4$ erg, such as energies of crystal ledges (200 erg), heat of wetting (10,000 erg) surface energies in bubbles or droplets (40 to 400 erg), biological energies in metabolism ( $\sim$ 10,000 erg), cataytic energies ( $\sim$ 10,000 erg), all order of magnitude.

A further conclusion of the energy criteria follows: zero-g affected reactions are limited to the liquid state where energies of reactions in solids are of the order of $10^5$ cal per mol, and in the gaseous stage (except at cryogenic energies) of the order of $10^4$ - $10^5$ cal therefore completely masking gravity effects.

Figure 2 summarizes the results of the energy criterium.

| mgh FOR 1 cc OF WATER | REACTIONS AFFECTED BY ZERO-G | |
|---|---|---|
| $E_g = 1.8\ 10^4$ erg | CRYSTAL GROWTH | 200 ergs/cm² |
| $= 4.2\ 10^{-4}$ cal | WETTING | 1000 ergs/cm² |
| | SURFACE ENERGY | 40-400 ergs/cm² |
| | BIOLOGICAL REACTION | 10,000 er |
| | CATALYTIC REACTION | 10,000 |
| | BUBBLES OR DROPLETS | 100-200 er /cm² |
| mgh = 0 | LEVITATION, INSTABILITIES | |
| NO EFFECTS IN SOLID OR GASEOUS PHASES | | |

FIGURE 2 CHEMICAL REACTIONS IN ZERO-G

## Energy Scaling Laws of Zero-G Processes

Scaling of potential zero-g processes leads to scaling laws, expressed in dimensionless forms, to so-called $\psi$-numbers shown in Figure 3. They can be expressed in ratios of energy or forces. Some of these ratios have names, such as Reynolds numbers (inert vs. viscous energy), Bond, McGrew, Tribus numbers.

$$\psi_1 = \frac{F_p}{F_g} = \frac{p\ell^2}{\ell^3\rho g} = \frac{p}{\ell\rho g}$$

$$\psi_2 = \frac{F_g}{F_\gamma} = \frac{\ell^3\rho g}{\ell\gamma} = \frac{\ell^2\rho g}{\gamma} = \text{Bond No.}$$

$$\psi_3 = \frac{F_{2\gamma}}{F_g} = \frac{\alpha \frac{\partial T}{\partial \ell} \ell^2}{\ell^3\rho g} = \frac{\alpha}{\ell\rho g}\frac{\partial T}{\partial \ell} \cong \frac{\alpha T}{\ell^2\rho g}$$

$$= \text{McGrew No.}; \ \psi_{3\,\text{Sphere, Bubble}} = \frac{2\alpha}{(\rho_\ell - \rho_2)gr}$$

$$\psi_4 = \frac{F_{2\gamma}}{F_{2V}} = \frac{\alpha \frac{\partial T}{\partial \ell} \ell^2}{\ell^2\mu \frac{\partial V}{\partial n}} = \frac{\alpha}{\mu}\,\frac{\frac{\partial T}{\partial \ell}}{\frac{\partial V}{\partial n}} \cong \frac{\alpha\theta}{\mu\ell}$$

$$\psi_5 = \frac{F_a}{F_V} = \frac{\ell^3\rho a}{\ell^2\mu \frac{\partial V}{\partial n}} = \frac{\ell\rho a}{\mu \frac{\partial V}{\partial n}} = \frac{V\ell\rho}{\mu} = \text{Reynolds No.}$$

$$\psi_6 = \frac{F_T}{F_V} = \frac{\ell^3\beta\rho g\partial T}{\ell^2\mu \frac{\partial V}{\partial n}} \cong \frac{\ell\beta\rho g T\theta}{\mu} = \text{Tribus No.}$$

| | | |
|---|---|---|
| $\ell$ = length | p = pressure | $\alpha$ = thermal coeff. of $\gamma$ |
| a = acceleration | T = temperature | |
| $\theta$ = time | $\mu$ = viscosity | $\beta$ = volume expansion coefficient |
| n = direction normal to flow | $\gamma$ = surface tension | |
| V = velocity | $\rho$ = density | g = 981 dynes |

FIGURE 3 DIMENSIONLESS RATIOS FOR SCALLING ZERO-G PROCESSES

Although usefulness of these numbers is somewhat limited, the value of those numbers is to gain confidence in simple predictions, overlooking many other physical factors. Consider the following question: "How large a sphere of a specific material can be formed at reduced g-level?" A Bond number smaller than unity shows that surface energy dominates over gravitational energy, and a stable condition exists.

$$\psi_2 = F_g/F_\gamma = 1 \text{ or } \ell = (\gamma/\rho g)^{\frac{1}{2}}$$

where $\ell$ is the dimension of the sphere. Figure 4 is a plot of this relationship showing the maximum size of the (stable) sphere for materials ranging from liquid helium to water as a function of fractional g.

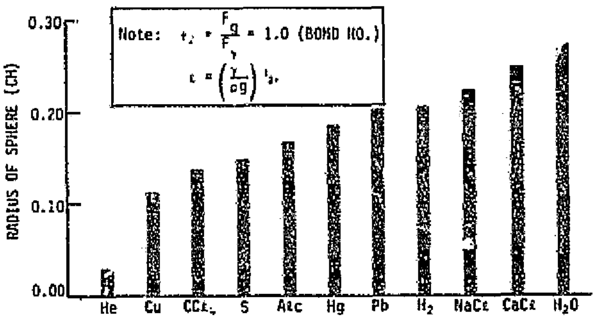


FIGURE 4 SIZE OF A PERFECT SPHERE FORMED IN AERO-G OF VARIOUS MATERIALS

Another application answers the question: "How closely must temperatures be controlled and how long would the forming process take in zero-g for a perfect steel sphere, for example?" The answer comes from the dimensionless numbers $\psi$-3 and $\psi$-4.

The role of $\psi$-numbers, although limited can be compared to that of the Reynolds number is hydrodynamics, e.g., it serves for classifying zero-g processes.

## Stability Criteria

Zero-g processes are characterized by the elimination of the gravitational energy in chemical processes; in addition, in space, a vacuum is available, which leads to elimination of atmospheric pressure, if so desired.

Under these conditions, fluids tend to become unstable. Instead of being bound to the form of a container, they may levitate and break up in droplets, where surface tension becomes the only cohesive force.

Two thermodynamical functions describe the chemical reactions (see Figure 5).

The free energy or Helmholtz function, F,

$$F = E - TS$$

and the Gibbs function, G,

$$G = E - TS + pV$$

where E is the energy, T temperature, S entropy, p pressure and V volume.

Stability requires that

$$(\Delta F)_T \geq 0; \ (\Delta G)_{T,p} \geq 0$$

| | |
|---|---|
| HELMHOLTZ FUNCTION | CONSEQUENCES FOR STABILITY |
| $F = E-TS$ | $\left(\frac{\partial T}{\partial S}\right) > 0 - \frac{\partial p}{\partial V} > 0$ |
| GIBBS FUNCTION | |
| $G = E-TS+pV$ | IN ZERO-G, ZERO-PRESSURE (VACUUM) |
| STABILITY CRITERIA | $\left(\frac{\partial V}{\partial p}\right) > 0$ |
| $(dF)_t \geq 0$ | OR INSTABILITY BEGINS, TO CONTINUE |
| $(dG)_t \geq 0$ | UNDER NEGATIVE PRESSURE. SURFACE |
| | ENERGY COUNTERACTS LEADING TO |
| | DROPLET FORMATION OR FOAMING. |

FIGURE 5 SECOND LAW OF THERMODYNAMICS - STABILITY CRITERIA

In Figure 5 we show that consequently the change of volume versus pressure should be negative, to satisfy stability. In zero-g, under absence of hydrostatic pressure (and eventually atmospheric pressure), these conditions lead to instabilities, e.g., exploding of liquids into droplets under the action of internal bubble formation or foaming.

These instabilities are characteristic for zero-g chemical reactions and bring into play small energies, as listed in Figure 2. They trigger reactions which are difficult to obtain in one-g environment. Many of those reactions, like undercooling in glass making, are thermodynamically unstable and have better chances to take place in zero-g.

## Hole Theory of Liquids

As well known, liquids are characterized as partially crystallized, but interspersed with facancies or holes of various sizes. This leads to the property of liquidity, i.e., the lack of a liquid to form its own geometrical shape like a solid, except for droplets under the influence of the surface energy. Pressure for a liquid is defined as positive, if it acts outside/in (like atmospheric or hydrostatic pressure) or negative, if it acts inside/out (boiling). Furthermore, at positive pressures in the range of $10^4$ to $10^5$ atmospheres, liquids reduce their volume by about 10% due to the vanishing of the holes; conversely at zero-g, zero-pressure (vacuum), expansion begins, becoming fully instable at higher negative pressures (see Figure 6).

Endothermic chemical reactions are more difficult to start than exothermic ones, often needing to be triggered by small energies. Sometimes they take place under boiling conditions, i.e., negative pressures. Again for normal chemical reactions, at high temperatures and pressures, as in a cracking tower, zero-g cannot add to the process. However, processes under small energy exchanges can be affected by zero-g when triggering secondary effects lead to appreciable chemical energies.

TAITS LAW: $V = V_0 - C_1 \log(1 + p/C_2)$; VANDER WALLS LAW $\left(p + \frac{C_3}{V^2}\right)(V - C_4) = RT$

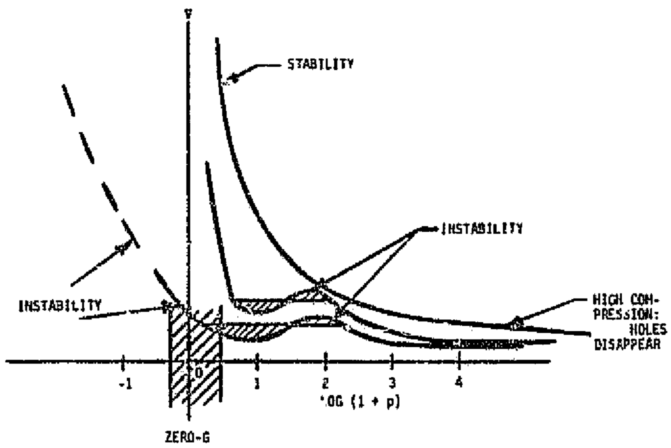


FIGURE 6 PRESSURE - VOLUME LAW FOR ZERO-G, ZERO-PRESSURE

Consider the sequence of the holes or vacancies in a liquid. Acceleration forces, like agitation, create bubbles, the macroscopic form of the holes. This cavitation process unleashes an amazing energy chain (see Figure 7), e.g., water has a surface tension of $\gamma = 0.08$ joules/m$^2$. Thus, each cm$^2$ of bubble surface has a potential energy of $8.10^{-6}$ joules. In one-g, the hydrostatic pressure, in zero-g the surface tension compresses this energy into the volume of a few molecules. These energy concentrations produce locally temperatures of 1000°C, or pressures of 10,000 atmospheres and violent chemical reactions set in, called cavitation.

| ENERGY | PRESSURE |
|---|---|
| $E_s = 2\gamma/r$ | $p/p_0 = e^{2\gamma v/rkt}$ |
| $\gamma$ = 80 WATER | |
| $\gamma$ = 400 MERCURY | $\log p/p_0 = 4$ |
| $r = 10^{-8}$ cm | $p = 10{,}000\ p_0$ |
| $E_s = 5.10^{-13}$ erg/MICRO BUBBLE | $p = 10^4$ kg/cm$^2$ |
| PER MOL: | CAVITATION, BOILING AND ZERO-G |
| $E_s$ = 10,000 CAL/MOL | BUBBLING ARE SIMILAR EFFECTS |

FIGURE 7 ENERGY CONTENT OF BUBBLES AND DROPLETS

Due to the importance of amalgams for zero-g manufacturing, let's follow this process for mercury instead of water. The surface energy of a bubble in mixing silver powder and mercury is

$$E_s = 4\pi\gamma r^2, \text{ with } \gamma = 400 \text{ erg};$$

$$r = 10^{-8} \text{ cm}; \ E_s = 5.10^{-13} \text{ erg}$$

This small value should not mislead us because when multiplied times the Avogadro number it yields an energy approximately 10,000 calories/mol, for a theoretical bubble size of 1 Å.

Similarly, the pressure reaches amazing high values. From the distribution law for a droplet, we know

$$p/p_0 = e^{-(E_s - E_0/kT)} = e^{2\gamma v/rkT}$$

where $p$ is the bubble pressure, $p_0$ the outside pressure, $E_s$, $E_0$ the corresponding energy, $v$ and $r$ the volume and radius of the bubble; it follows for a minimum bubble of 8 molecules (8 neighbors to form a sphere)

$$\log p/p_0 = \frac{8\gamma\, r^2}{kT}$$

and taking

$$\gamma = 100 \text{ erg/cm}^2; \ r = 4.10^{-8} \text{ cm}; \ T = 300°\text{K};$$

$$\log p/p_0 = 4; \ p = 10^4 \text{ kg/cm}^2$$

Similar value occurs in liquids locally in boiling up.

In zero-g conditions, when the vacancies are increased by lack of hydrostatic pressure and the surface tension takes over, instabilities result, with secondary energy effects furnishing energy for endothermic reactions such as occurs in boiling. (See Figure 8)

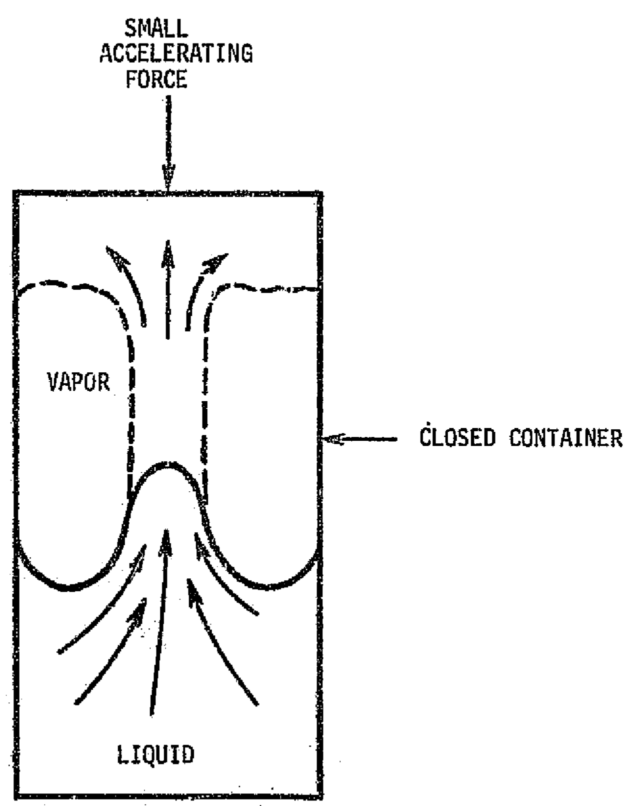


FIGURE 8 ZERO GRAVITY HYDRODYNAMICS

Instability

Figure 9 shows the basic instability of a liquid surface, by comparing it to a bent elastic wire or spring. The surface energy is potential energy stored and can be released if triggered properly. Kelvin's law states that heat is absorbed when the surface is increased (specific heat of surface).

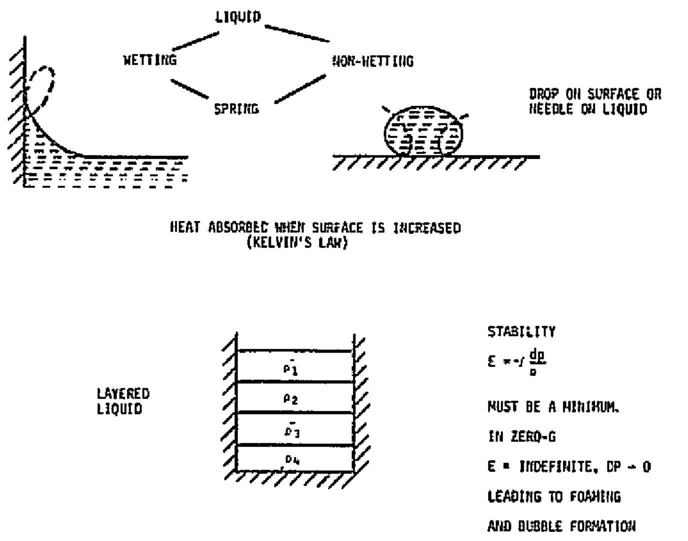


FIGURE 9 SURFACE TENSION INSTABILITY

Similarly, if we consider lowering of liquids of different density - stability by a gravitational field as given only if the energy corresponds to the minimum potential function

$$E = -\int dp/\rho$$

In zero-g, the liquids form bubbles, remains spread over the surface (wetting), depending on Dupré's law of the adhesion energy

$$E_{ad} = \gamma_1 + \gamma_2 - \gamma_{1,2} \lesseqgtr 0$$

(compare Literature 2 and 5).

Catalysis

Many endothermic reactions depend on catalysis (see Literature 7), i.e., the presence of a participant in a chemical reaction, which remains unchanged at the end of the reaction. Metal oxides, like iron oxide, molybdenum and platinum oxide are used as such.

Their action depends on their ability to readily accept and reject electrons, e.g, valence electrons. The catalyst changes during the reaction valence levels and returns to the original state, like the spring type action of lasers of masers, only at much smaller energy levels.

Energy levels of such valence electrons of metals, and electron affinites of non-metals are in the order of magnitude of

$$1 \text{ eV} = 1{,}6 \times 10^{-12} \text{ erg.}$$

This is about the same order of magnitude as the energy in the micro-bubbles, $10^{-13}$ erg, we found in the Kirkendall vacancies of liquids. Again, multiplying by Avogadros number, we reach energies of 10,000 cal/mol and more.

Although accepting and rejecting electrons by a donor catalyst has nothing to do with gravity, the energy levels involved are commensurate with gravity energies. Thus, low pressure, low temperature catalytic reactions, like enzymatic relations will be influenced by gravity.

ZERO-G - APPLICATIONS AND PRODUCTS

Levitation and Glass Making

Glass is an undercooled liquid in a metastable state. In zero-g, the metastable state can be easier obtained and preserved by levitation, i.e., avoidance of contact with container wall surfaces and ensuing impurities which serving as embryos to start crystallization, bubbles or Griffith cracks during quenching.

Rate of crystallization of an undercooled liquid is influenced by colloidal particles on the walls, serving as crystallization centers. Wetting by the wall furthers crystallization. Ionization at the surface again induces crystallization.

The degree of supercooling which can be reached, before crystallization occurs, and the liquid becomes a solid glass depends on the previous heat treatment of the system. The longer the liquid has been kept, before cooling, at a temperature $T_2 > T_o$ (the melting temperature), and the higher this temperature, the lower the temperature $T_1 < T_o$ it can withstand without crystallization. This amounts to a destruction (i.e., melting) of various foreign particles, which would otherwise act and release energy like bubbles, with a higher melting point $\leq T_2$, which, if they remain intact, could serve by bubble-like energy release as crystallization centers.

Glasses have a "memory." Residual crystals formed at the end of a quenching process preserve - at certain places at least, near the wall of the container - an invariable orientation, as if they "remembered" orientation which they acquire in the course of the preceding crystallization.

The zero-g application of this process is two-fold:

- Achieve the glass state by undercooling under levitation conditions, without wall contacts. This can produce larger blanks of conventional glass, or can obtain glass states of high refractive insulators such as $Al_2O_3$, $ZrO_2$, $HfO_2$, $TiO_2$ which would otherwise crystallize in one-g.
- Achieve a glass state with "memory," i.e., a glass, which will crystallize after remelting in a perfect way, since impurities are refined out. This subsequent crystallization can take place in one-g on Earth, as long as the memory formation has been done in zero-g.

Crystallization

Crystallization leads to different products,



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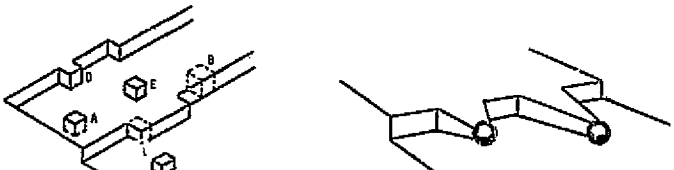
namely, perfect crystals (e.g., diamonds); wiskers and platelets, a product of imperfect crystals.

Crystallization is condensation from the liquid phase (even if formed from the vapor phase, a liquid phase is interposed). This condensation occurs on edges, kinks, ledges of the crystal, where energy is concentrated, (see Figure 10). The average energy on such energy concentrations is 20-200 ergs/cm$^2$ leading to gravity influence according to the energy conservation theorem.




CRYSTAL SURFACE SHOWING ENERGY CONCENTRATIONS:
A - IN SURFACE
B - IN LEDGE
C - KINK
D - AT LEDGE
E - ABSORBED IN SURFACE

AVERAGE LEDGE ENERGY: 200 ERGS/CM$^2$

LIQUID DROPLETS IN CONTACT WITH A MACROSCOPIC STEP, LEADING TO MORE RAPID GROWTH

FIGURE 10 ENERGY CONCENTRATIONS ON PERFECT CRYSTAL SURFACES

Perfect crystals are formed in absence of convection currents. Forty (see Literature 8) found that the bending energy of convection currents, about 400 ergs, is equal to the energy necessary to break a platelet, i.e., an embryo crystal. However, in zero-g, although there are no convection currents due to absence of buoyancy forces, there are still Marangoni flows (see Figure 11), driven by surface tension gradients. To avoid Marangoni flows, bubbles have to be eliminated from the melt carefully.

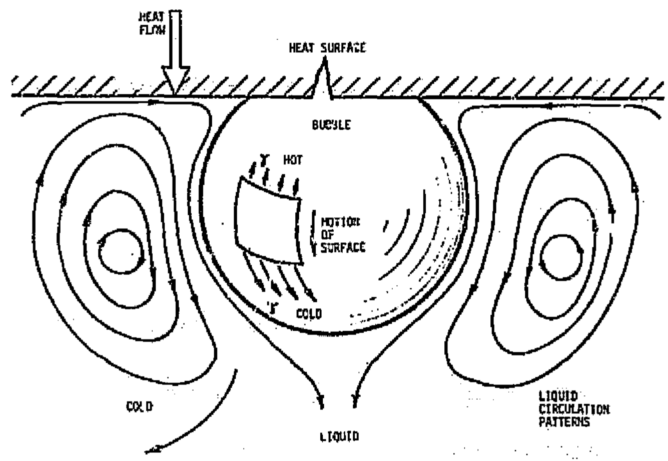
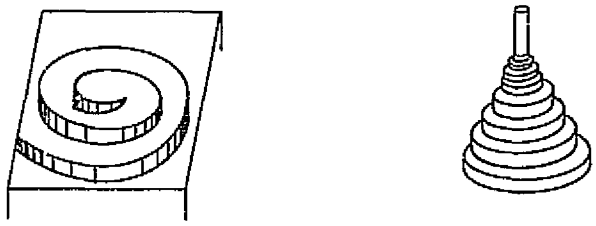



FIGURE 11 THE MARANGONI EFFECT

Imperfect crystals are formed along linear surface energy concentrations, of order of $10^{-4}$ erg/cm - again per mol a respectable number. Dislocations represent such surface energy concentrations. If they form spirals, whiskers result (see Figure 12).



SPIRAL DISLOCATION LEDGE ON A GROWING CRYSTAL

AVERAGE ENERGY $\geq$ 50 TO 250 ERG/CM$^2$

WHISKER EMANATING FROM SPIRAL DISLOCATIONS - GROWTH CONE

FIGURE 12 ENERGY CONCENTRATIONS ON IMPERFECT CRYSTALS SURFACES

Wetting

Many applications, such as composites from fibers, metal - metal oxide sinters (e.g., Aℓ - $Aℓ_2O_3$ ), superconductors ($Nb_3$ Aℓ $Nb_3$ Ge, $Nb_3$ Sn) depend on wetting of insoluble alloy components. The resultant material is either a high strength structural element Aℓ - $Aℓ_2O_3$ or Fe - Fe S or a new electric ceramic element.

After applying the heat of wetting, e.g., approximately 4.4 x $10^4$ ergs/cm$^2$ for silica powder, total wetting occurs. Zero-g has the beneficial effect, that gravity does not affect the thickness of wetted layer as in one-g.

A Helmholtz function describes the heat of wetting

$$F = S \quad \gamma_{ad} - T \frac{d\ \gamma_{ad}}{dT}$$

where $\gamma_{ad}$ is the adhesion tension of the clean solid against the liquid, S the surface.

Again, wetting energies are commensurate with gravitational energies.

Other possible applications are emulsification, flocculation and "frothing" (mineral flotation). In essence, these processes are one-g simulations of zero-g processes widely used in industrial chemistry for separation of otherwise inseparable components, by making them "swim" regardless of gravity differences. Obviously, in zero-g a much wider field of applications opens up for separating in the emulsion or foam state of otherwise inseparable reaction products (see Literature 4).

The production of poly water (polymerized water) in capillaries is another form of wetting (see Literature 9).

Cavitation

One of the most potent applications in zero-g is cavitation. They embrace: new amalgams and light weight structures by metal foams.

We have shown that cavitation occurs in zero-g and frees surface energy for chemical use. Obviously, other amalgams can be created, such as Pb-Cu; Pb-Fe, a class of new metal lubricants; or amalgams, matured in zero-g, creating materials of high tension yield and not only compression yield like one-g silver-mercury amalgam. In the case of amalgams, the bubbles are used to create energy for the endothermic formation of new alloys.

In the case of forms, this process is interrupted by flash freezing. The bubbles are preserved. Cooling of homogenous or controlled density foams is possible since the lack of buoyancy prevents bubble concentrations.

Electrolytic Effects

The free atoms on a surface, e.g., of a bubble foam a natural surface condensor (see Literature 4) with a charge of $zen \approx ze/r^2$ where $e$ is the electron charge, $z$ the valency of the atom and $n$ the number of atoms per unit area at distance $r$.

The capacity of the double layer formed by the free atoms is $C = 1/4 \ \pi r$ and the stored energy

$$E_d = \frac{2e^2}{8\pi r^3} \sim \frac{Ze^2 n}{8\pi}$$

This contact potential is in the order of a few volts with the energy $E_d$ of a few hundred ergs/cm$^2$.

Freezing such a liquid creates built-in electric charges, similar to semiconductor effects (holes in the electric sense). In zero gravity, such "electrets" can be formed.

Another electric effect is the formation of bubbles by electric charges, e.g., in a hydrogen bubble chamber (see Literature 3). There, the hydrostatic pressure has to be in equilibrium with the vapor pressure generated by the capture of elementary particles.

In zero-g, in absence of a hydrostatic pressure, much bigger bubbles result from less energetic particles, or - the sensitivity of a bubble chamber increases.

Liquid Crystals

Liquid crystals are polymers in liquid form, acting like crystals (see Figure 13). They are used for peripheral computer equipment as light shutters reacting to electric fields for fast printers.

Liquid crystals have been known for about 100 years and only recently emerged from scientific curiosity items to applications. They are polymers, subject to viscosity.

In zero-g, viscosity is reduced (see Literature 4), due to the increase size of the holes (vacancies). Thus, manufacture of "cybotactics"- the scientific name of liquid crystals, to higher degree of ordering is indicated.

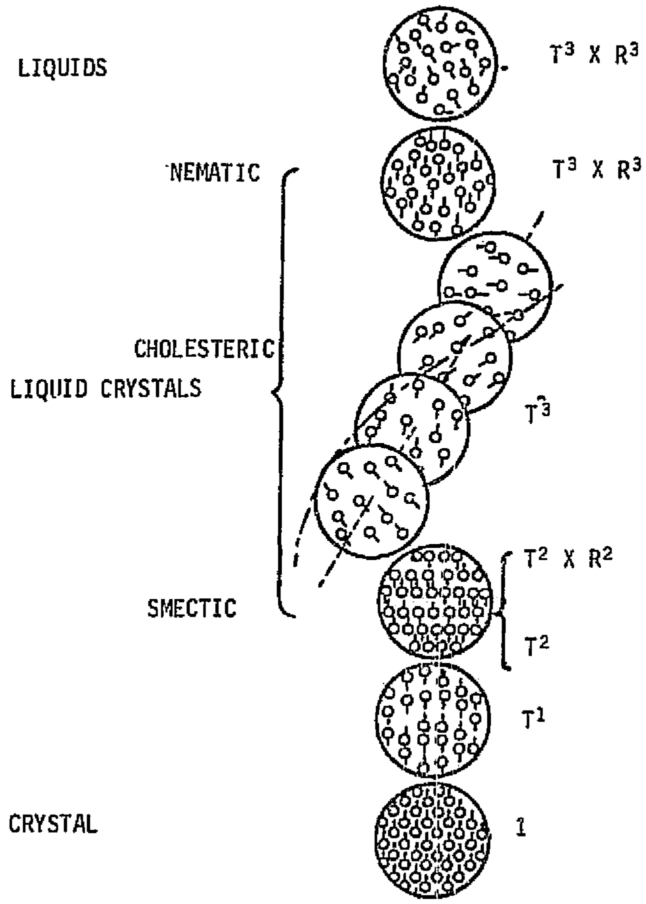



FIGURE 12 ENERGY CONCENTRATIONS ON IMPERFECT CRYSTAL SURFACES

Enzymes and Vaccines

Enzymes are biological catalysts. Enzymes contain metal atoms; their valence changes cause the catalysts effects of enzymes in either oxidation or hydrogenation.

Biological processes (see Figure 14) depend on oxygenation for metabolism, with energies of 8000 cal/mol; however, the long chain of metabolic in-between products is affected by much smaller energy amounts, at the same order of magnitude as corresponding gravity energies.

Thus, it is not surprising that biological growth processes and gravity are connected. The embryo in a mother's womb, the chicken embryo inside the egg are in "neutral buoyancy" or zero-g state.

Some of the biological processes are foaming processes, i.e., the use of bubbles for energy transfer like permentation. Figure 15 shows the size of the bubble energy transfer - $\psi$-4 - for alcohol fermentation.

Therefore, zero-g may open a field of accelerated biological growth. Data from Biosatellite II indicates faster bacterial growth rates and the latter effect could be attributed to radiation damage.

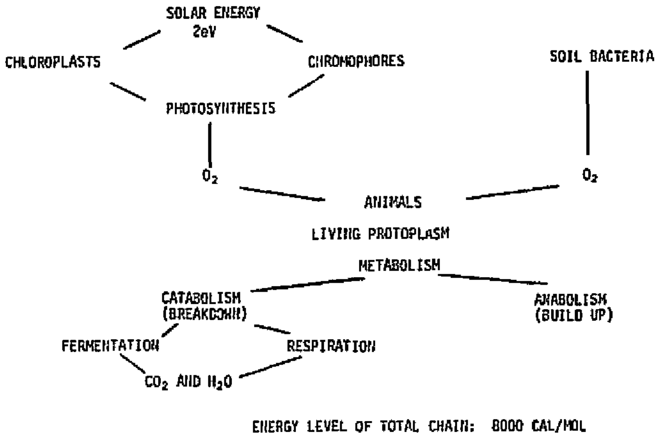



FIGURE 14 CHAIN REACTIONS IN METABOLIC PROCESSES

Fermentation by dialysis (a form of osmosis) has led to consideration of a vaccine fermentor for zero-g (see Figure 16). The nutrient has to be oxidized by oxygen bubbles of the finest distribution possible to create the maximum surface for diffusion of oxygen to the fermentation product. In zero-g this is possible, since the lack of hydrostatic pressure allows much smaller bubble size.

It is expected, due to additional side-effect avoidance (such as overfeeding or central necrosis) to increase the speed and yield of vaccine growing over the speeds and yields obtained in one-g production (by inocculation of eggs or in aerators).

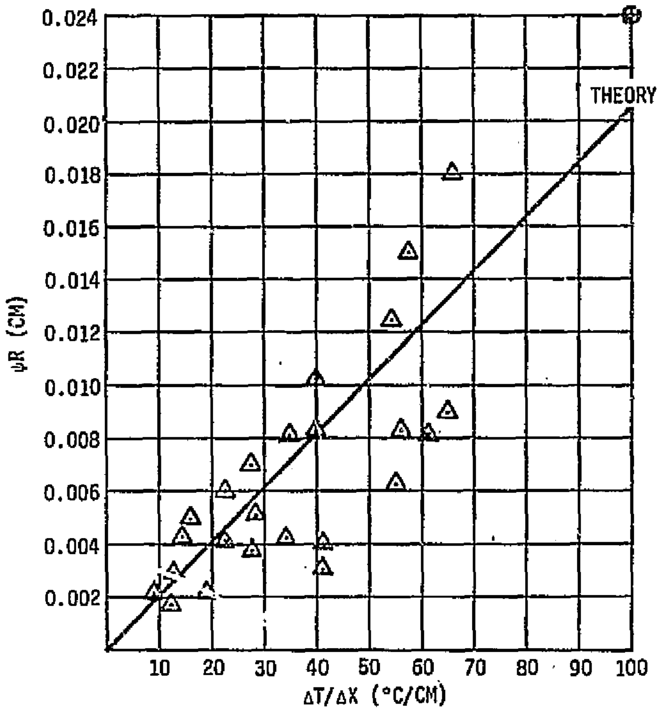



FIGURE 15 BUBBLE FORCE PARAMETER VS LIQUID TEMPERATURE GRADIENT (TEST LIQUID, N-BUTYL ALCOHOL)

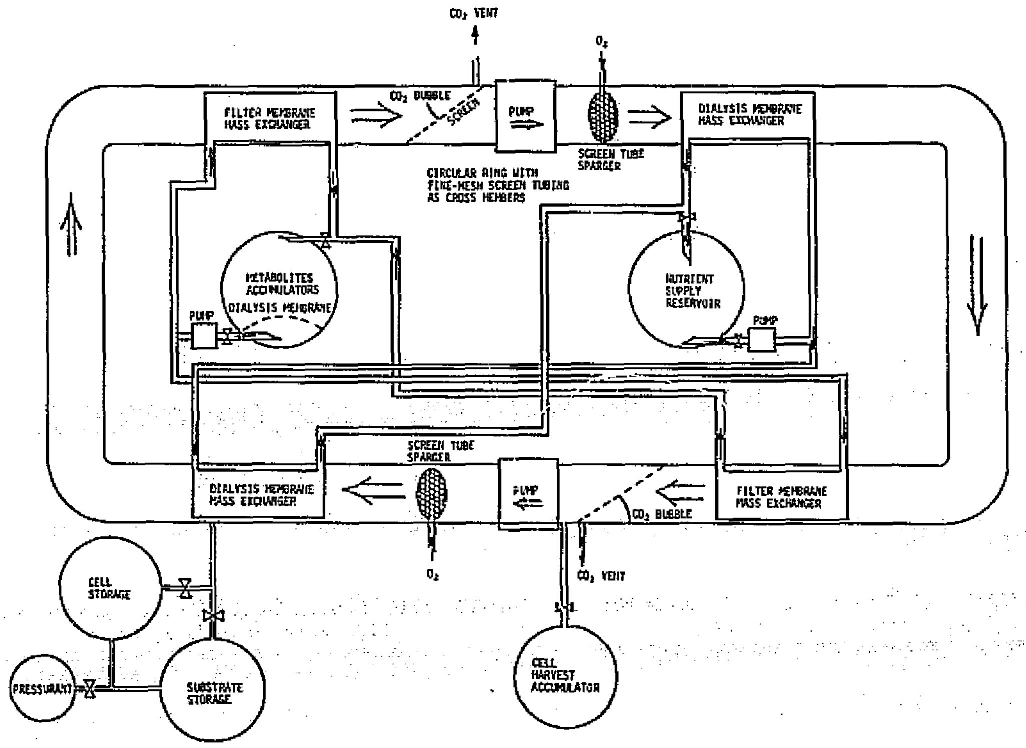



FIGURE 16 A ZERO-G FERMENTER DESIGN, FLOW CIRCULATION LOOP CONCEPT

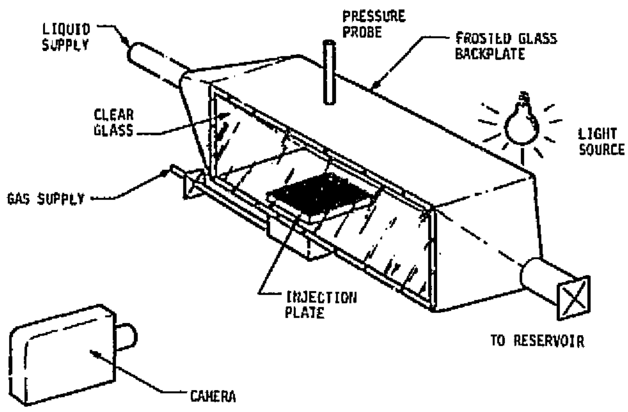



FIGURE 17 BUBBLE INJECTION TEST AP" :ATUS

Figure 17 shows the bubble generator to obtain quasi solution of oxygen in the nutrient (e.g., chicken broth). The suspension of fine cxygen bubbles in the nutrient is stable in zero-g, unstable in one-g.

## INSTRUMENTATION FOR ZERO-G MANUFACTURING

In Figure 18, a tentative list of zero-g manufacturing is shown. This is the complement to the processes described in the foregoing pages.

| | PRODUCT CLASSES | AERO-G PROCESSES | ENERGY LEVEL (GIBBS FUNCTION) IN ORDER OF MAGNITUDE/MOL |
|---|---|---|---|
| DIRECT ZERO-G EFFECTS | | | |
| | GLASSES | LEVITATION | -- |
| | COMPOSITES | WETTING | $10^{-3}$ CAL |
| | SINTERS | WETTING | $10^{-3}$ CAL |
| | CRYSTALS | ABSENCE OF BUOUANCY | $10^{-3}$ CAL |
| | MATERIAL SEP-ARATION | FROTHING/FLOTATION/ ELECTROPHORESIS | $10^{-3}$ CAL |
| INDIRECT ZERO-G EFFECTS | | | |
| | METAL FOAMS | BUBBLE FORMATION | $10^{4}$ CAL |
| | AMALGAMS | CAVITATION | $10^{4}$ CAL |
| | LOW TEMPERAURE/ PRESSURE ENDO-THERMIC REAC-TION | CATALYSIS | $10^{4}$ CAL |
| | BIOCHEMICAL REACTION | ENCYME/FERMENTATION | $10^{4}$ CAL |

FIGURE 18 ZERO-G MANUFACTURING PROCESSES

Before one embarks to build a complete facility for a specific product which fulfulls the necessary condition of higher dollar value per pound, one will experiment in a "general purpose" laboratory. The list in Figure 19 covers the equipment for such a laboratory. Of course man as experimenter is involved in the use of this instrumentation to create the product desired.

Even in the case of automating a specific product chosen, man still will be interacting in product control, maintenance and equipment reconfiguration.

FURNACES

- MELTING FURNACE/CAPTIVE SUSPENSION
- MELTING FURNACE/FREE SUSPENSION
- ADHESION CASTING FURNACE
- CONTROLLED DENSITY CASTING FURNACE
- SURFACE TENSION CASTING FURNACE

CHAMBERS

- DEPOSITION CHAMBER - GALVANIC/VAPOR
- CHEMICAL REACTION CHAMBER (VACUUM)
- ELECTROPHORESIS CHAMBER
- FERMENTATION/DIALYSIS CHAMBER
- CRYSTAL GROWTH CHAMBER

COOLING

- AUTOCLAVE
- QUENCHING FACILITIES

FIGURE 19 SPACE MANUFACTURING FACILITIES IN DWS-2

## CONCLUSION

Potential and possible space manufacturing processes are characterized by the fact that the reaction energies involved are of similar or equal magnitude as the gravitational energies of the reactants in one-g.

Scaling laws are developed to allow the steps from small to larger production units.

Gibbs functions for the processes are shown in order of magnitude. They are small amounts of energies, serving as triggers for chemical reactions, otherwise suppressed by gravitational energies.

On this basis, 37 new product classes for zero-g manufacturing are described - many proposed before, some described here for the first time.

One of the most potent and hopefully most useful zero-g manufacturing products may be vaccines for the benfit of mankind from space technology.

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# POSITIONING AND HANDLING IN WEIGHTLESS ENVIRONMENT

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## ABSTRACT

After experimental verification on the first and second orbital workshops, manufacturing processes suitable for industrial application will emerge. The flight facility environ for this use will contain functional elements simi.. to those employed in manufacturing on earth.

Several electro-mechanical devices to transfer, position and retrieve space manufacturing equipment are discussed. Application to an orbital manufacturing facility is described.


## INTRODUCTION

Previous speakers have dealt with manufacturing processes which employ weightless environment of space flight to create new and unique products. Following experimental verification of such processes, pilot plant operations in space will emerge. Eventually, a complex of space stations devoted entirely to creation of useful products may evolve from ideas similar to those described today.

Writing in the January 23, 1967 issue of Technology Week, Isaac Asimov stated: "Mankind is now faced with the practical need for working under low gravity conditions and technologists will have to develop "low gravity engineering", in consequence. The day for that is coming; it is clearly ahead, and the problems it brings will be like nothing experienced in the past."

Unique products from space will be available in quantity only when low gravity engineering provides the tools and facilities to support the emerging low gravity materials processing technology.

Like its counterpart on earth, the space manufacturing plant will have to accommodate supporting tooling to the process requirements within a suitable facility.

Gravity dependent tooling techniques used on earth to move and position objects cannot be used in space. Frictional forces between objects disappear with the absence of the uni-directional force gravity or dead weight. Well known proposals for positioning and handling objects in the neutral stability conditions of space include remotely controlled jet propelled tugs, extendable booms and truss-like structures. A new approach to space handling systems is to mechanically connect objects with a linkage which provides the means to propel, guide, stabilize, rendezvous and dock. (Reference 1, 4)

This type of device consists of a number of powered links which may be actuated relative to each other. Controls at the fixed or free end will be operated to extend the device in a straight or serpentine configuration as required to transport, rendezvous, and dock objects at tip. This serpentine actuator is called a serpentuator.

The serpentuator will be designed to impart approximately 1/100 g to objects at the tip. Between two and four pounds force is estimated to be adequate to move an object with 200 to 400 pound mass in space.

The serpentuator replaces the earth floor which serves to position and locate objects and assists in translation of men and materials. Thus the space plant can be as large as its space floor, which is equal to the volume reached by a serpentuator system.

Figure 1 illustrates how a space manufacturing plant may consist of a number of tools and processing units positioned outside but near the actual manned quarters. These modules would be brought inside or docked with the parent space station for loading and service. Captive or free flying modules would be deployed to proper orientation for gravity gradient for particular processes as well as to assist in dissipation of heat generated during a manufacturing process. In addition, a serpentuator could also serve as a remote inspection and repair system for the entire space station and serve to transfer men and materials between adjacent spacecraft.

The serpentuator system could be used to locate and position a vacuum refinement module adjacent to the parent space station. (Reference 5)

Calculations indicate vacuum of the order of $10^{-15}$ torr exists in the wake of objects orbiting at about 500 kilometers. While earth vacuum systems can equal or approach space vacuum of $10^{-9}$ torr, none have been able to achieve that available in the wake of an orbiting object. Figure 2 shows how experimental verification of calculations could be done using a serpentuator system. (Reference 8)

In addition to conducting parametric studies on roles and missions for serpentuators in Apollo program (Reference 12), the Marshall Space Flight Center Manufacturing Engineering Laboratory has fabricated and tested feasibility and engineering models of several designs of serpentuators.

The first model was built to verify control and positioning accuracy in a single plane. Test hardware of a hand powered hydraulic model to be used in the first Saturn workshop was built and evaluated. A full size, eight link, forty foot length serpentuator to assist in ATM film retrieval was built for evaluation in underwater simulation. The latest engineering model uses a hermetically sealed electromechanical hinge to prevent outgassing of lubricants and permit sterilization. A short description of each of the model serpentuator follows.

FIVE-LINK FEASIBILITY AND DEMONSTRATION MODEL

The model serpentuator was built several years ago to demonstrate in a single plane how objects in space might be relocated without expending mass.

Each link of this electro-mechanical model employs surplus DC electro motors and ball screws to provide hinge motion. See Figure 3. Figure 4 shows the fixed base link and four movable links. It may be operated from the base control console or the tip link using the same control box.

Links are activated sequentially by limit switches sensing maximum angular travel of adjacent links. Link motion started either at tip or base will continue until stopped by end limit switches or at some point by the operator. Multi-link devices in general require a feedback system and rate control of the angular motion between links in order to be controllable. The need for such a complicated control system can be avoided by sequencing so that only one link moves at a time. Restriction of freedom between links to single plane motion and with only one rotary joint at the attachment base allows the free end to reach each point in a spherical motion volume. Two steering modes provide sufficient flexibility by either starting the link motion from the base gimbal end or from the free end.

The force available to move the links is proportional to the deflection of the control stick. Links can move 20 degrees and return. These links were considered typical for 100 foot serpentuator to be stored and launched in the unpressurized area of a 33 foot diameter booster. (Reference 9)

DESCRIPTION OF DEMONSTRATION MODEL OF HAND POWERED HYDRAULICALLY OPERATED SERPENTUATOR

This serpentuator was designed for possible use within an early Orbital Workshop to assist the astronauts in transferring various items from their launched position in the MDA to the walls of the empty S-IVB booster. The astronauts would move the folded serpentuator through the forty inch diameter removable hatch in the forward bulkhead, clamp it to internal structure, then by controlled deployment, transfer objects from the hatch entrance to predetermined locations on the tank walls. Figure 5.

This demonstration model was hand powered, hydraulically operated and could be controlled from either fixed or free end.

General specifications for this serpentuator were:

1. Total Length - 18 feet.
2. Number of links (including base link) - 5.
3. Length of each link - 3.6 feet.
4. Total End Force - 6 pounds.
5. Fold into maximum envelope not to exceed 39.75 inches in one dimension.
6. The base link would contain a "roll" actuator.
7. Incorporate quick-disconnect base attachment.
8. Control system would consist of on-off valves controlling flow from hand pump to hydraulic rotary actuators.

One tip link and one link actuator separated by a fifteen foot tabular spacer was built to evaluate the design and human factors. Evaluation and testing was conducted on air bearings and in water (Figure 6) by suited operators.

Test results included:

1. Folded serpentuator could be handled and attached in low gravity by one man.

2. Directed movement could be accomplished by operator at tip.

3. Operator fatigue could be reduced by a hydraulic system requiring a small number of relative high force pump strokes rather than numerous low force, high frequency strokes. Operators in astronaut suits reported the effort to overcome suit restraint more fatiguing than operating the pump. Unsuited subjects in air and water found movement and control easy and not fatiguing.

4. Off the shelf rotary hydraulic seals have unacceptable leakage for space operations.

5. The need for a hermetically sealed powered hinge joint moving $\pm$ 180° movement established.

This design was not pursued further when the Orbital Workshop concept filled the S-IVB tank volume with multiple floors. (Reference 10)

## DESCRIPTION OF FULL SCALE ENGINEERING MODEL OF SERPENTUATOR TO TRANSFER FILM CASSETTES ON ATM

Past experience has shown that extra vehicular activity makes large demands on astronaut time and energy. This serpentuator was proposed to assist the astronaut in extravehicular activity which cannot be avoided. Retrieval and replenishment of film of the multiple cameras in the Apollo Telescope Mount is an example of unavoidable astronaut EVA. An astronaut will move himself and film cassettes about exterior of the AAP cluster using a combination of hand rails and foot holds.

Responsibility for moving the bulky film cassettes while preventing inadvertent collisions with ATM structure will require constant attention and effort. The astronauts task would be reduced if transfer of the film cassettes were separated from the effort of moving himself.

A remotely operated serpentuator could provide this assistance. To study the operational problems and rewards of this proposal, a full scale engineering model serpentuator will be evaluated in a neutral buoyancy facility on full scale ATM mock-ups.

The proposed serpentuator would be supported between the solar panels and sun shield on the Apollo Telescope Mount. Figure 7 illustrates how the eight link serpentuator would be deployed from launch position on the octagonal shaped ATM.

Figure 8 shows the serpentuator positioned near the MDA EVA hatch to receive film cassettes. The serpentuator tip is remotely controlled to intercept the astronaut at the work station and solar end. Figure 9 shows one configuration assumed by the serpentuator enroute to the solar end of the ATM.

Changes in the AAP program have altered some details of the 1/20 scale model configuration but the illustrations are still realistic because the position of the MDA and film service locations are unchanged.

Figure 10 shows the 40 foot serpentuator being evaluated on air bearings. The base actuators are attached to the octagonal mount which will simulate the ATM attachment during underwater testing. Individual rubber bellows cover each hinge joint to permit pressurizing the interior of the serpentuator. The tip control box is also pressurized. The astronaut support and film cassette holders for underwater testing are not shown.

The seven powered hinges move 0 - 45° and all links move in a common plane. Each hinge is actuated by a linear ball screw driven by an electric mechanical gear train. The an[illegible] actuation is 1 RPM maximum, to assure low tip velocity. Actuator torques are made larger than required for space operations to assure adequate power for underwater simulation. The three outboard link actuators produce 40% smaller torques than the inboard link actuators.

Yaw and roll actuators are provided at the base to allow tip to reach any point in the water volume. Figure 11 shows the base roll and yaw actuators. Each actuator can produce 450 foot pounds of torque with a maximum angular rate of 1 RPM.

Both actuators are direct current electro-mechanical, employing harmonic drive units. The roll actuators rotate $\pm$ 200° while interference with the mounting frame restricts the base yaw actuator to $\pm$ 120°.

Roll, pitch and yaw actuators are mounted outboard the tip link to provide final positional adjustments similar to wrist movements in conjunction with the relatively gross movements of the upper arm.

The eight-link 40 foot serpentuator will be manually controlled from either fixed or free end. TV scanning and angular readouts on each link will permit operator at fixed end to develop a repeatable sequence of motions required to move the cassettes between required points on the cluster. (Reference 11)

## ENGINEERING MODEL OF SERPENTUATOR HAVING HERMETICALLY SEALED ACTUATORS.

Greater reliability of components operating in space can be expected if the components are operating in an earth like environment than in the space environment. Existing technology with proven performance can be used if earth temperatures and pressures can be created in space. Metal bellows are a potential solution to enclose the pressurized hinge linkage. However the reliability of bellows flexing more than a few degrees while under small internal pressure is not well established since bellows typically are used without pressure and with modest linear motion.

This program sought to develop a reliable electromechanical hinge which could operate $\pm 180^{\circ}$, be packaged in a cylindrical container less than five inches in diameter, be hermetically sealed and produce about 50 foot pounds of torque.

Figure 12 shows the power train and linkage which meets the above specification. A DC motor driven ball screw operates the linkage which can move $\pm 180^{\circ}$.

Figure 13 shows the two hinged model built for testing. Serpentuator actuators are controlled remotely from a separate control box or from switches in the base link. Links are operated separately and motion is the same direction as switch is operated.

Figure 14 shows how a serpentuator made from 8 links could be folded into a 13 1/2 cubic feet volume. The serpentuator would be 38' long. The sketch also shows how pitch and roll motions could be achieved without use of actuators employing rotary seals. (Reference 6, 13)

## CONCLUSIONS

The serpentuators described constitute the preliminary system analysis and design of alternate approaches to one concept for positioning and locating objects in a space manufacturing plant.

Current and future in-house efforts will refine component and system performance to provide design specifications for flight hardware.

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(10) Contract NAS 8-20707, Astro-Space Laboratories, Inc., Huntsville, Alabama, 1967.

(11) Contract NAS 8-30036, Astro-Space Laboratories, Inc., Huntsville, Alabama, 1968.

(12) Contract NAS 8-21279, Martin-Marietta Corp., Denver, Colorado, 1969.

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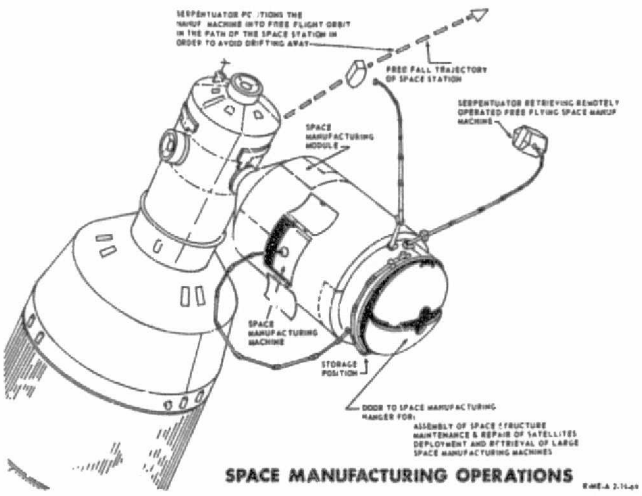



Figure 1. Space Manufacturing Tools and Modules Positioned and Handled by Serpentuator.

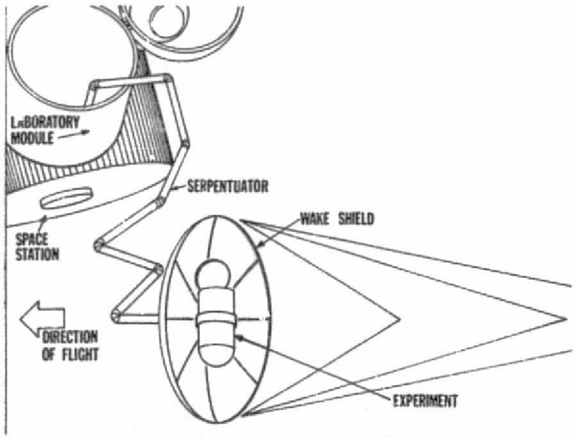



Figure 2. High Vacuum Refining Module Positioned and Handled by a Serpentuator.

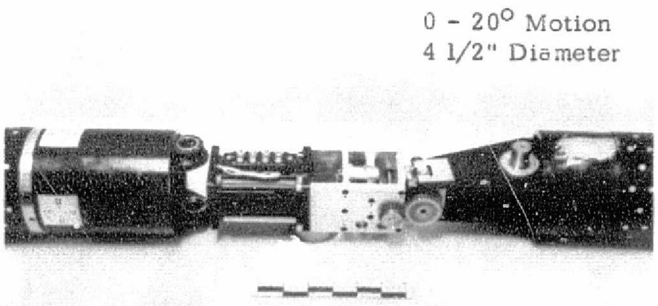



Figure 3. Typical Hinge Actuator of Five Link Model Serpentuator.

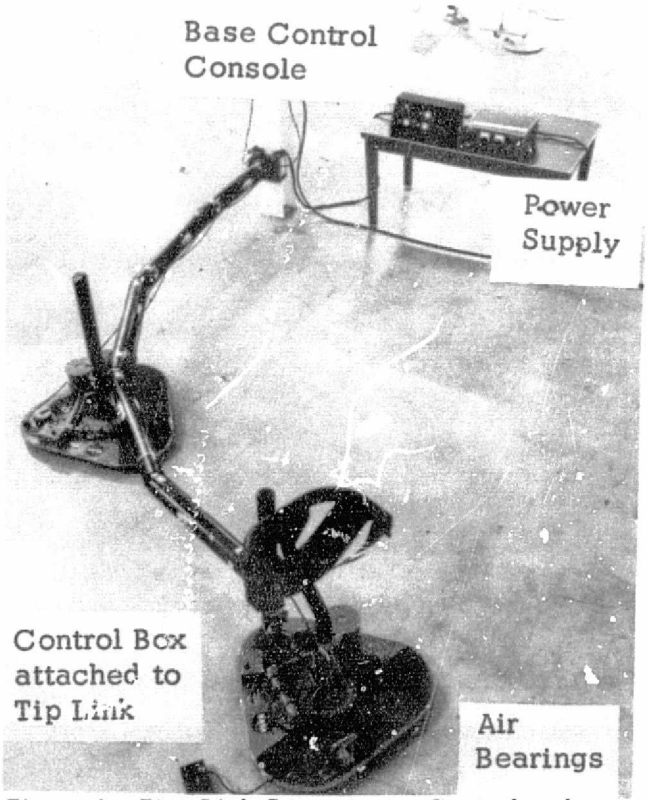



Figure 4. Five Link Serpentuator Control and Positioning Accuracy Evaluation on Air Bearings.

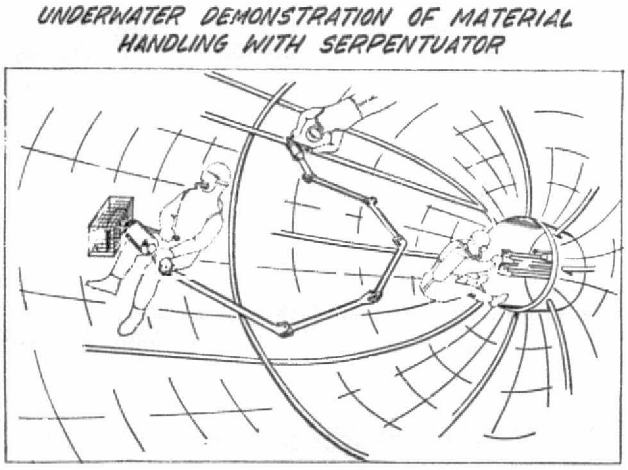



Figure 5. Concept of Portable, Hand Powered, Foldable Serpentuator.

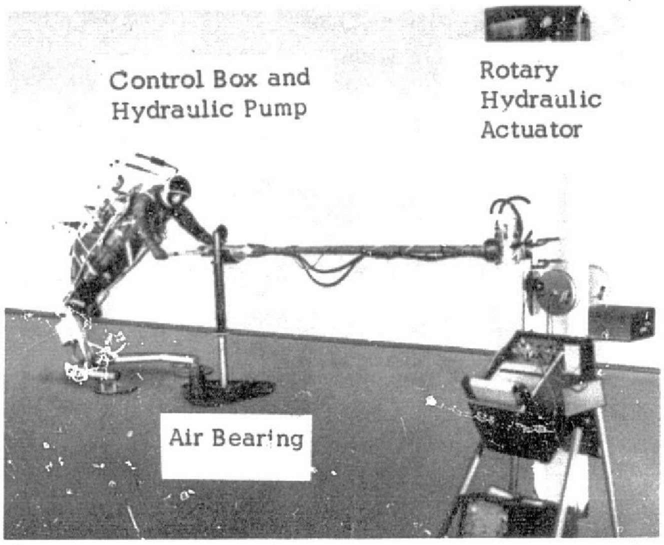



Figure 6. Human Factors and Design Evaluation of Hand Powered Serpentuator.

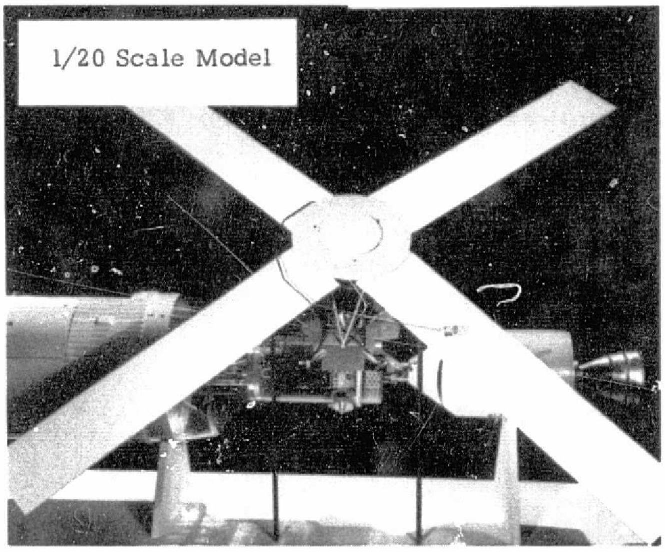



Figure 7. Initial Deployment from Launch Position of Forty Foot, Eight Link Serpentuator.

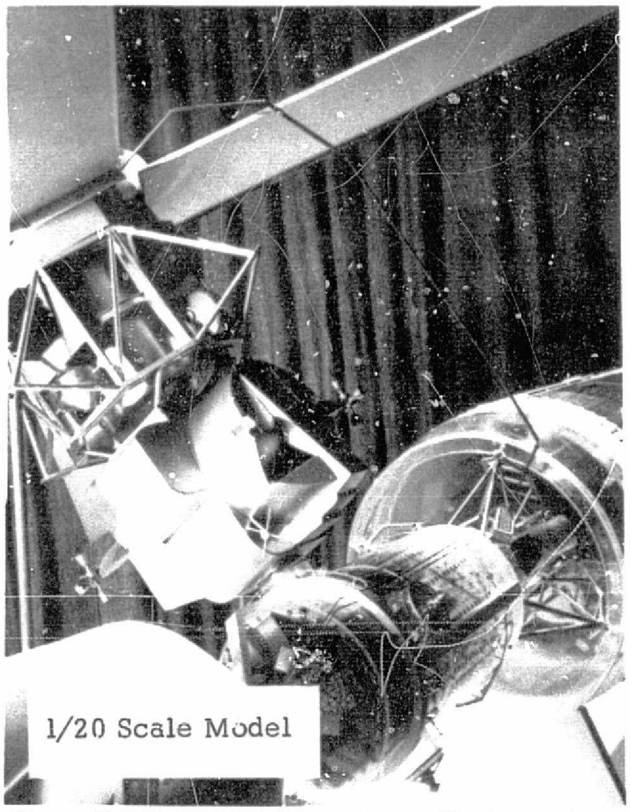



Figure 8. Forty Foot Serpentuator Tip located near MDA Egress Hatch.

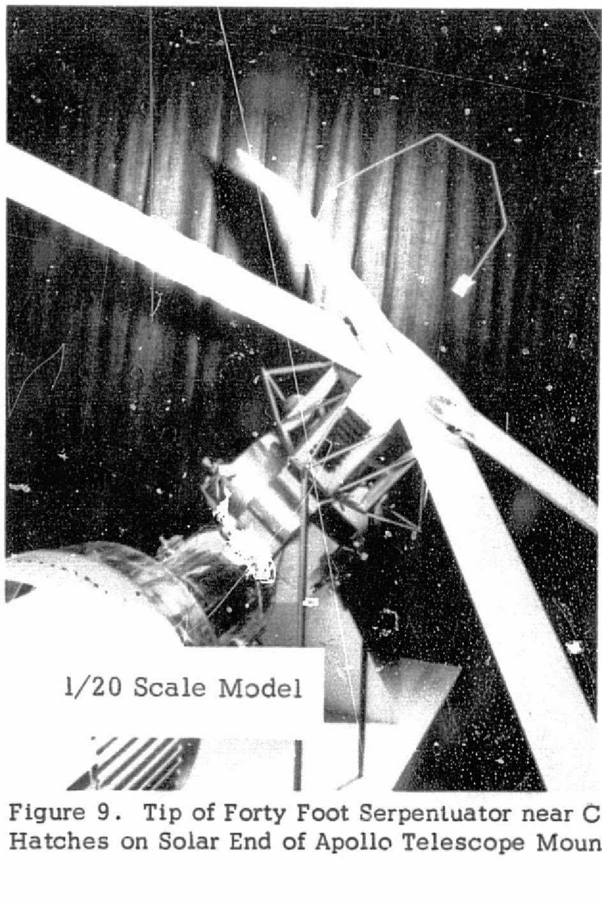



Figure 9. Tip of Forty Foot Serpentuator near Camera Hatches on Solar End of Apollo Telescope Mount.

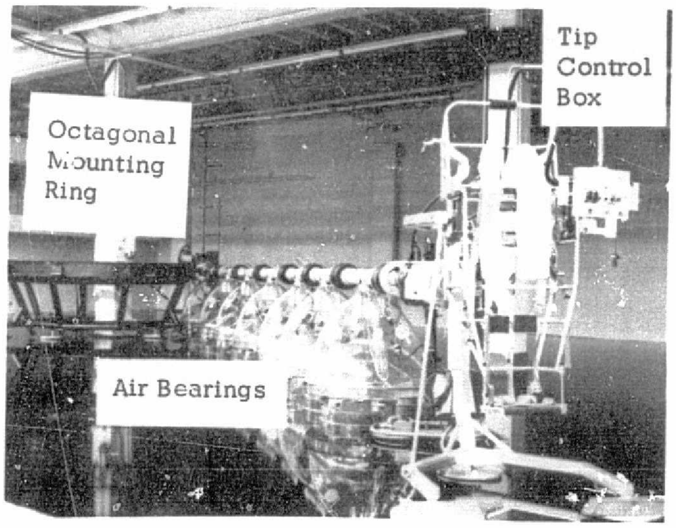



Figure 10. Forty Foot Serpentuator Control and Design Evaluation on Air Bearings.

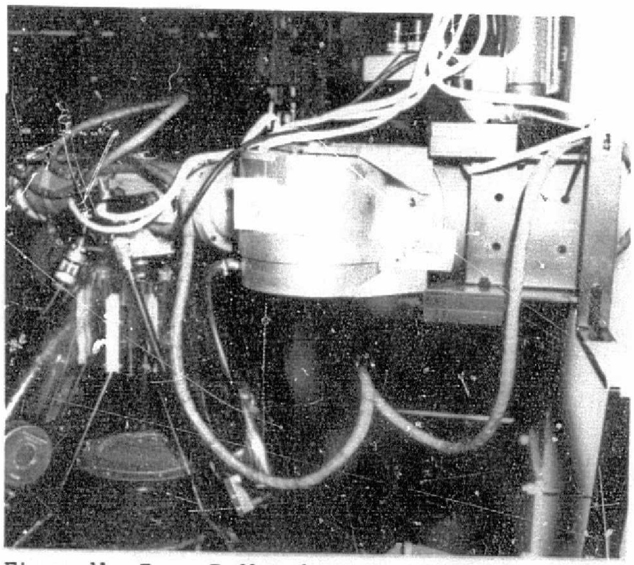
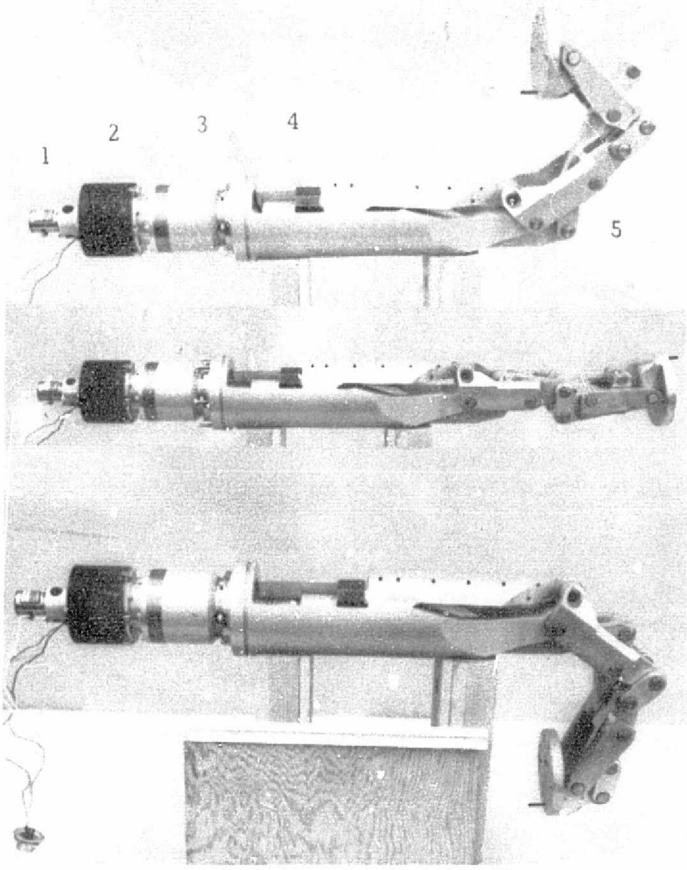


Figure 11. Base Roll and Yaw Actuators on Forty Foot, Eight Link Serpentuator.




1. Magnetic Brake
2. DC Motor
3. Harmonic Drive Unit
4. Ball Screw Operated Bell Crank
5. $\pm 180^{\circ}$ Travel Linkage

Figure 12. Mechanism of Hermetically Sealed Serpentuator Hinge.

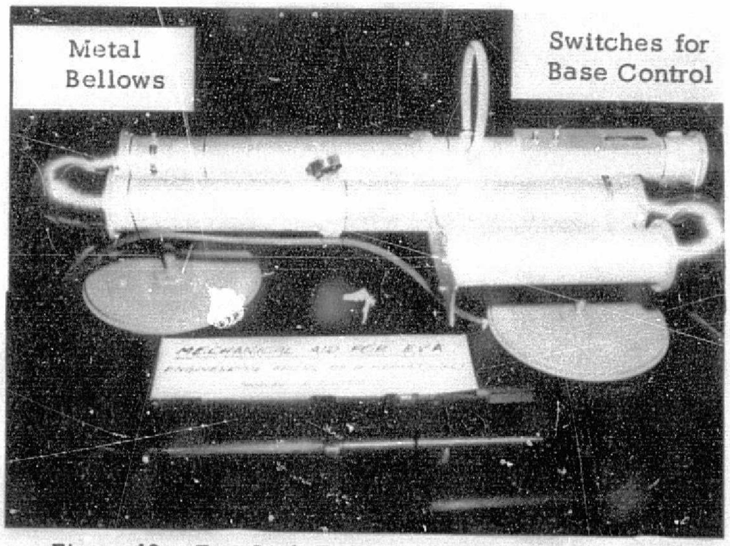



Figure 13. Two Link Test Hardware of Hermetically Sealed Serpentuator.

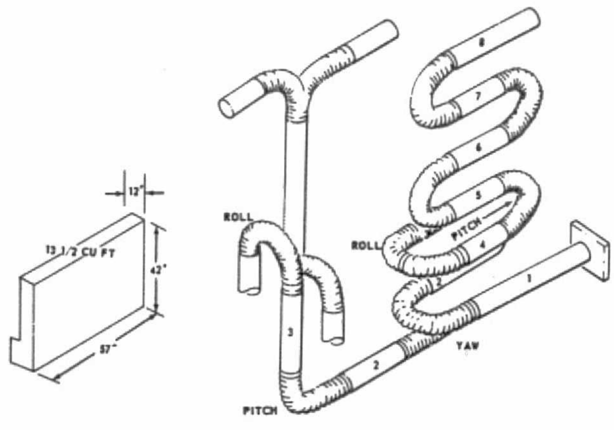



Figure 14. Hermetically Sealed Serpentuator with Three Degrees of Motion.

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