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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_{g_E} and by applied forces ΣF_{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).

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*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 Δr the radial distance from the mass center. (Ref. 4.) Above the mass center, the distances Δr at which certain g-levels are encountered are as follows.

Distance Δr (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 3×10^{-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 σ, as used here and later, is more accurately the interfacial tension between the liquid and gas phase, identified by σ_{LG}. There are likewise interfacial tensions σ_{LS} and σ_{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 β, the liquid will only spread out until uniform curvature has been attained. If β 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

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

In the process of formation of the sphere from a nonspherical 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

$$t \simeq \frac{1 + \sqrt{1 + \frac{4\sigma\rho R}{\mu^2}}}{2\,\frac{\sigma}{R\mu}} \qquad (9)$$

ρ = density
σ = surface tension
R = radius
μ = viscosity

which may for most liquids be simplified to

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

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 τ required for the initial amplitude to decay to 1/e are represented by the relationships

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

$$\tau = H_\tau \frac{\rho}{\mu} \cdot D^2 \qquad (11)$$

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

$$F_{Deform} = F_{Surf.\,Tens.} + F_{Pressure} + F_{Inertia} \tag{12}$$

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

$$F_{Hold} = \frac{\sigma}{R} A \tag{13}$$

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 ω for the achievement of a specific distortion δ from the spherical shape is represented by the relationship

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

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 manufacture is done in space in a special facility consisting of a melting chamber, a feeding and mixing system, and exchangeable molds.

In large-scale production, extravehicular 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 minimun-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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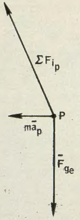


Figure 1. Definition of g.

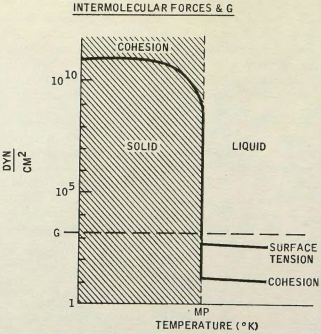


Figure 3. Intermolecular Forces and g.

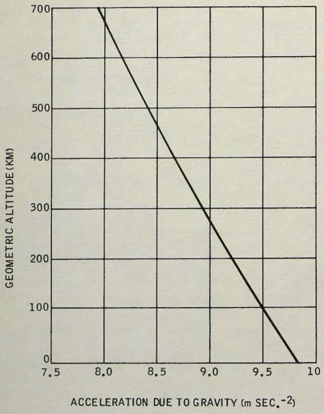
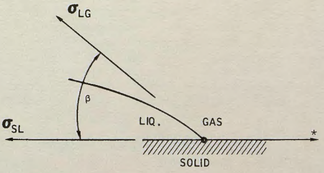


Figure 2. Acceleration Due to Gravity g as a Function of Geometric Altitude.



$$* \longrightarrow \sigma_{SG} = \sigma_{SL} + \sigma_{LG} \cos\beta$$

OR, FOR $\beta = 0$ $\quad \sigma_{SG} \geq \sigma_{SL} + \sigma_{LG}$

Figure 4. Surface Tension.

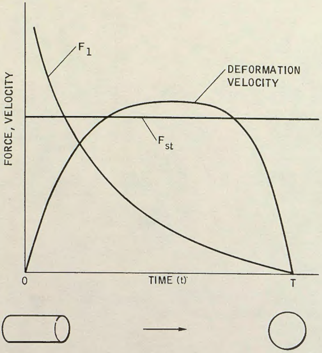


Figure 5. Variation of Forces and Deformation Velocity for Transformation of a Liquid into a Sphere.

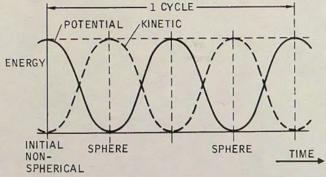
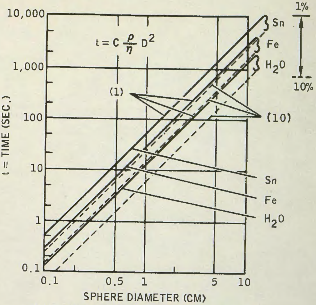


Figure 6. Sphere Oscillations in Terms of Potential and Kinetic Energy (Relationships 6 and 7 Represent the First One-Quarter Cycle).



TIME t TO DAMPEN OSCILLATION OF SPHERE TO 10% & 1% OF ORIGINAL AMPLITUDE

Figure 7. Dampening of Sphere Oscillations.

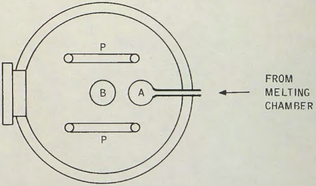


Figure 8. Processing of Liquid Spheres.

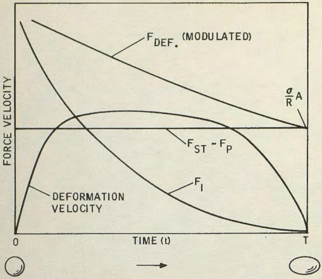


Figure 9. Variation of Forces in Contact-Free Liquid Forming (Modulated Forming Program).

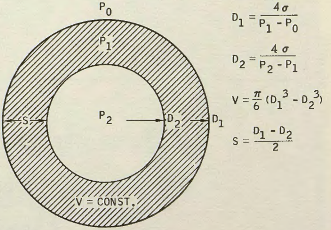


Figure 11. Pressures and Dimensional Characteristics of Thick-Wall Hollow Spheres.

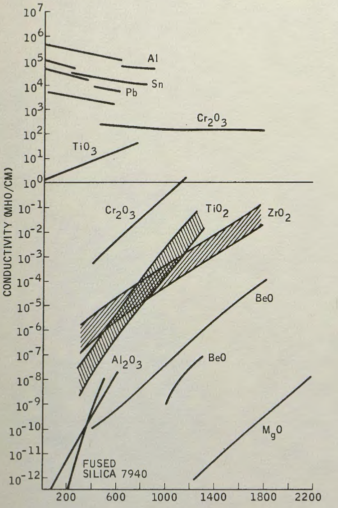


Figure 10. Electrical Conductivity of Material versus Temperature.

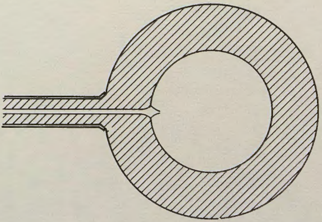


Figure 12. Dual-Nozzle Deployment System for Thick-Wall Hollow Spheres.

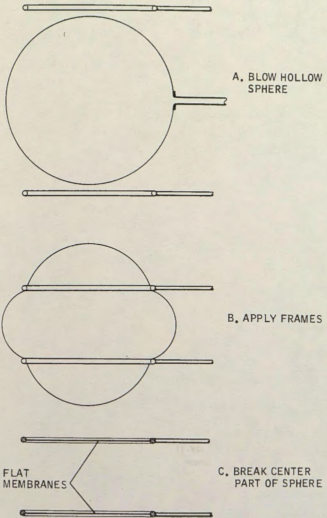


Figure 13. Formation of Flat Membranes from Hollow Spheres.

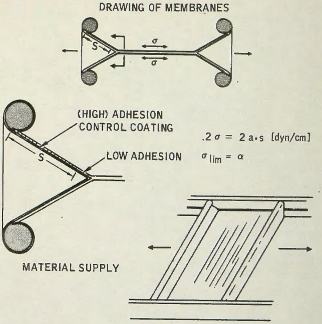


Figure 14. Drawing of Membranes.

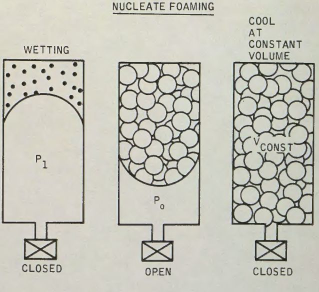


Figure 15. Nucleate Foaming.

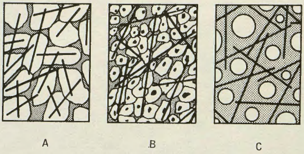


Figure 16. Microstructures of Modified Cast Composites.

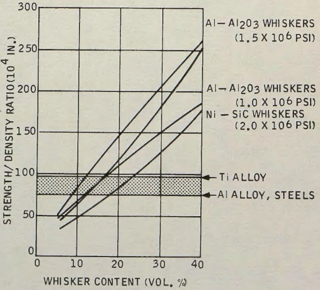


Figure 17. Strength of Cast Composites in Comparison with Conventional Materials.

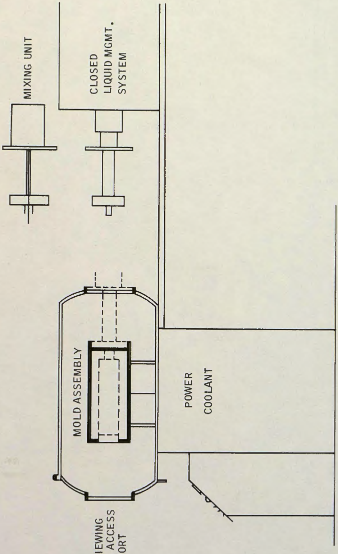


Figure 18. Mold-Casting Chamber b.

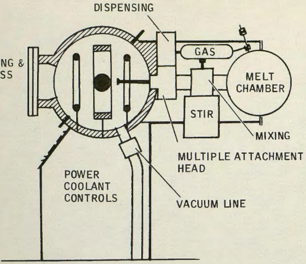


Figure 19. Free-Processing Chamber b.

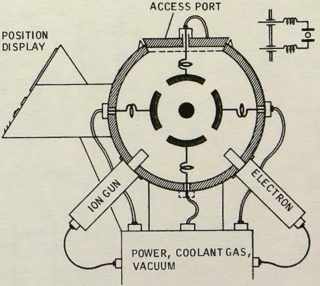


Figure 21. Electrostatic Positioning and Melting Chamber C.

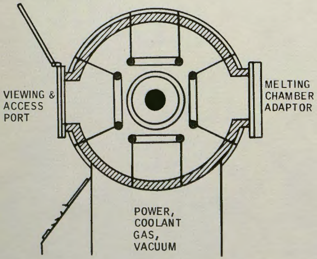


Figure 20. Free-Processing Chamber B.

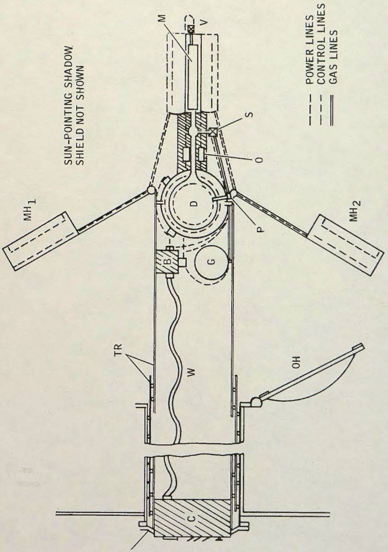


Figure 22. Attached Mode — Extravehicular Experiment.

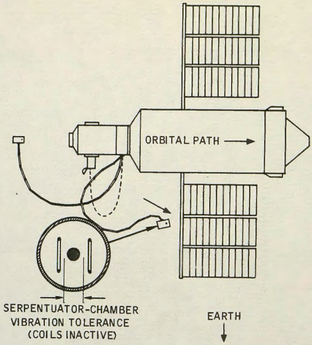


Figure 23. Extravehicular Operations by Means of the Serpententuator.

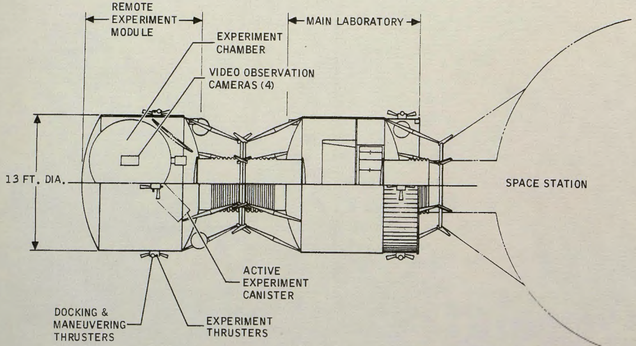


Figure 24. Space Manufacturing Module.

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	$Mg_5 Ga_2$	840		1
56.4	Al 43.6	$Al_2 Ga$	830		1
34 (32.8)	Cu 66	$Cu_9 Ga_4$	1,650	4	1
13	Ag 87		1,100		2
36.4	Sb 63.6	Sb Ga			2
27	Te 73	$Ga_2 Te_3$	1,450		1
36	Te 64	Ga Te	1,450		1
18	Au 82	Au_3 Ga (+Au)	840	5	1
22-27	Au 73-78	Au_3 Ga	790		1
34 (28-40)	Au 66	Au Ga_2 + Au Ga	900(+)	8	2
91	Li 9	Ga Li	(low)		3
32	44 Cu - 24 Sn		1,200	24	1
32	50 Cu - 18 Sn		1,290	24	1
33	44 Cu - 33 Au		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 crystalization 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 Isotopes

Table 4. Assessment of Relative Process Effectiveness.

PROCESSES OR 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	●	
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					○	○		●
3 Thick-Wall Hollow Spheres		I		●			●			◉
4 Thin-Wall Hollow Spheres		I		●			●			●
5 Flat Membranes	II	III					○			●
6 Foams & Cellular Materials		I	●			●				◉
7 Composite Casting		I	●			●				◉
8 Dispersed Particle Castings		II				●				◉
9 Supersaturated Alloys	I	II	○			●				◉
10 Thermosetting Alloys	I	II			○				●	●
11 Containerless High-Temp. Melting	II	III						○		●
12 Single Crystals		I			○		○		●	◉
13 Amorphous Materials (Glasses)	I	II			○			●		◉
14 Unit Separation Processes	I	II			○				●	◉

o Capability development experiments

● Process & product demonstration experiments

◉ Full-scale production experiments