UNIT OPERATIONS IN MICROGRAVITY

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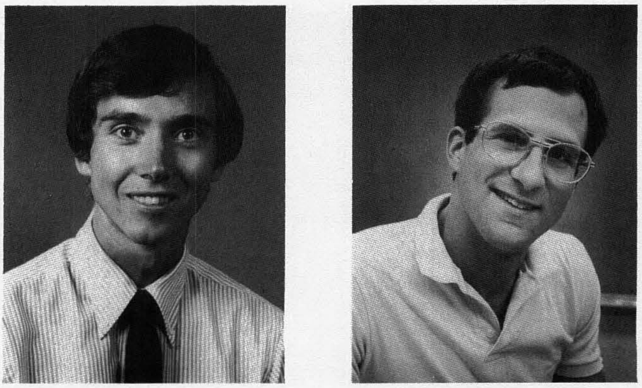
THE SPACE SHUTTLE and the planned space station offer unique envionments for chemical processing. The three basic advantages that space offers that are not generally available in earth-based systems are low temperature, high vacuum, and sustained periods of zero or microgravity. Ready access to low temperatures and high vacuum may allow for the development of processes requiring large structures in vacuum, long duration cryogenic cooling, or multiple vacuum to high pressure transitions. However, most of the unit operations that are being developed for materials processing in space are designed to take advantage of reduced gravity. The next few pages will present a brief review of some of the work currently under way in the development of microgravity processes. The material is largely based on a series of symposia held at AIChE meetings since 1985 [1, 2] and a group of NASA publications [3-5]. Our goal in performing this review is twofold. First, we seek to highlight some of the opportunities for materials processing in space, and second, we want to emphasize the contributions that chemical engineers can make in this emerging set of technologies.



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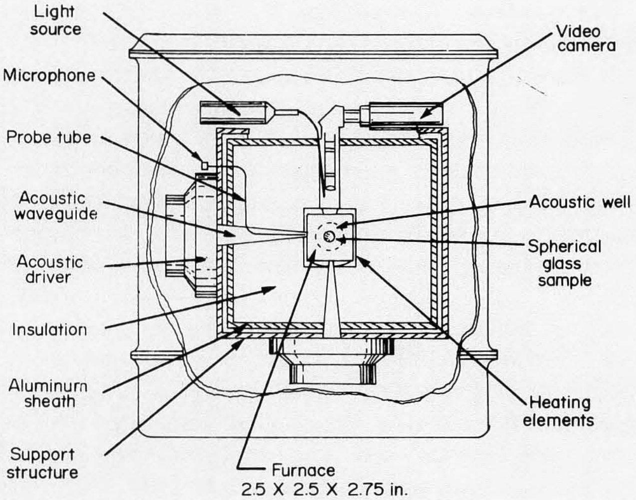

FIGURE 1. Containerless furnace based on acoustical levitation (ref. 6).

UNIT OPERATIONS IN MICROGRAVITY

A spacecraft orbiting the earth at an altitude of approximately 190 miles is only 6% farther from the center of mass of the earth mass than an object on the earth's surface. Thus, the gravitational force experienced by the spacecraft is only 13% less than the gravitational force at the earth's surface. However, because the spacecraft and all of the objects in it are in free fall, there is no gravitation acceleration of the objects in the spacecraft relative to the spacecraft. The objects are in an approximately weightless, or zero gravity, environment in the frame of reference of the moving spacecraft. But even in the spacecraft's frame of reference the gravitational force is not precisely zero. There are two types of gravitational force experienced in the spacecraft. The largest forces are induced by small vibrations in the ship (g-jitter), which can cause a gravitational force of order 10^{-3} g.

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G-jitter is roughly random and averages out to a zero net force. A constant force of order 10^{-6} g is caused by gravitation gradients. The gravitation force in low earth orbit changes at a rate of 10^{-7} g per meter as an object moves away from the center of mass of the spacecraft. In a spacecraft with a dimension of 10 m, a force of order 10^{-6} g can be imposed.

Reduced gravity allows two classes of unit operations to be used in space processing that are not generally available in a one-g environment. The first type of unit operation uses various means of levitation to achieve containerless processing, and the second type is based on the absence of buoyant and sedimentation forces.

CONTAINERLESS PROCESSING

In a microgravity environment objects levitate and will assume a conformation that minimizes interfacial energy. Thus, it is possible to contain liquids and to process solids without exposing the materials to vessel walls. The concept of levitation is not new, nor is it confined to microgravity environments. Indeed, Robert Millikan first measured the charge of an electron by levitating a charged oil drop in an electromagnetic field. However, the masses that can be levitated in an earth-based experiment are limited, and the levitating force can cause significant heating and distortion of the material. In a microgravity environment, levitating forces are imposed primarily to counter the small gravitational forces discussed earlier or to adjust an object's position. Much larger masses can be levitated in space than on earth, and heating effects are not as important.

Eletrostatic suspension, acoustic standing waves, photon beams, gas or vapor stream momentum, and magnetic induction have all been proposed as levitation mechanisms for containerless processing in space. The containerless processing apparatus that has seen the most extensive use on the space shuttle is acoustical levitation. If the object to be suspended can be exposed to a gaseous environment, acoustical drivers (loudspeakers) can be used to control the position of the object. In a typical configuration, three mutually perpendicular acoustical drivers are used to produce a 3-dimensional standing acoustical wave in a roughly cubical box (Figure 1) [6]. An energy well is created at a position dependent on the wavelength generated by the acoustical drivers. Containerless systems that can impose a desired shape on a deformable material are shown conceptually in Figure 2 [7]. These devices use gas momentum to suspend objects and could be useful in casting parts of arbitrary shape.

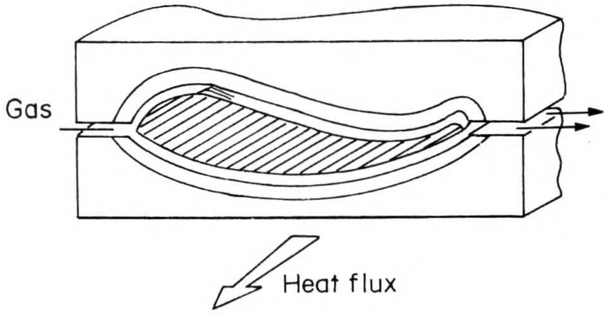

FIGURE 2. Conceptual configuration of a containerless process for casting unusual shapes (ref. 7).

The ability to levitate relatively large masses in microgravity has resulted in a number of applications. The primary applications have been in suppressing heterogeneous nucleation during crystal formation and in the production of new glasses and unusual alloys. Crystallization and the production of new glasses will be considered briefly in this review because they represent two quite different examples of containerless processing (*i.e.*, semi-containerless and truly containerless).

When a glass forming melt is suspended in a levitation device, heterogeneous nucleation is suppressed. The outgrowth of this phenomena is the ability to extend the compositional limits of glasses, making possible entirely new materials. One such class of materials is fluoride glasses, which have great promise as infrared optical components [8, 9]. A second possibility for generating unique materials by containerless processing in microgravity is the production of millimeter size glass shells with walls of thin, uniform thickness [10]. Many other applications are envisioned through the use of controlled gradient furnaces coupled with levitation devices.

These processes can be regarded as truly containerless. However, they are forced to operate in a batch mode. Semi-containerless unit operations can be operated continuously. One such process involves the crystallization of materials important in electronic devices and utilizes Czochralski growth (Figure 3) [5]. In this unit operation, a seed crystal is lowered onto the free surface of a melt. As the seed is withdrawn, the melt

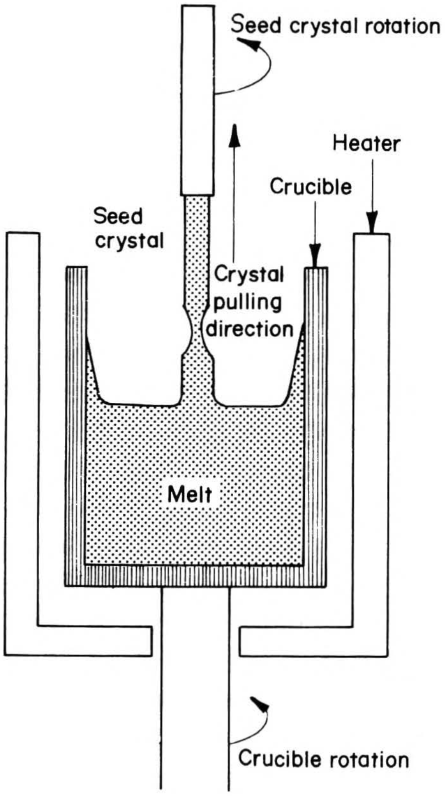

FIGURE 3. Semicontainerless process for crystal growth.

adhering to it solidifies. This unit operation can be performed in one g. However, less defects are present in crystals produced in microgravity than in similar crystals produced on earth. The defects in one g are due, in part, to convective stirring caused by the heat of crystallization. In microgravity, buoyant driven convective motion is significantly reduced. Problems associated with this unit operation in microgravity are contamination by impurities derived from the crucible and the difficulties associated with maintaining a flat melt surface in microgravity.

A second semi-containerless unit operation is float zone refining. Figure 4 shows a typical float zone crystallization configuration. The feed crystal, containing imperfections, is melted and then slowly recrystallized. The purpose of the float zone is to insure uniform dispersal of dopants, reducing imperfections. The float zone (melt) is suspended by interfacial tension between the feed material and the crystal. In microgravity, much larger float zones are possible than at one g and concentration inhomogeneities due to convective motion and growth spurts are minimized [11]. A new approach to float zone crystallization is shown in Figure 5. In this system [12] the crystallizing material is isolated by the float zones, and a seed crystal is not required.

UNIT OPERATIONS BASED ON REDUCED SEDIMENTATION AND BUOYANCY IN MICROGRAVITY

Sedimentation and buoyancy effects are greatly subdued in microgravity relative to one-g operation. This can be extremely advantageous in electrophoretic separations, making metal foams, and in the production of unique alloys. However, the absence of buoyancy makes some unit operations that are easily done on earth much more difficult. For example, removing bubbles from glasses [13], obtaining reasonable mass transfer rates in aerobic reactors, and even operating a distillation column become difficult. For the moment let's consider only the advantages of space processing by focusing on electrophoresis and the creation of new materials.

Electrophoretic separations are frequently used to isolate biological molecules and cells. The separation is based on the net charge obtained on molecules or cells when they are placed in a buffer solution. The ions in the buffer associate with the species to be separated, providing a net charge. An applied electric field causes an ionic current to flow and generates a force on the charged species. The charged molecule or cell moves with a velocity that balances the electrical force with viscous drag. Because the charge associated with particular molecules and cells are highly structure-dependent, different species will migrate at different rates, allowing them to be separated as shown in Figure 6. Like most of the unit operations discussed in this brief review, electrophoretic separations are not

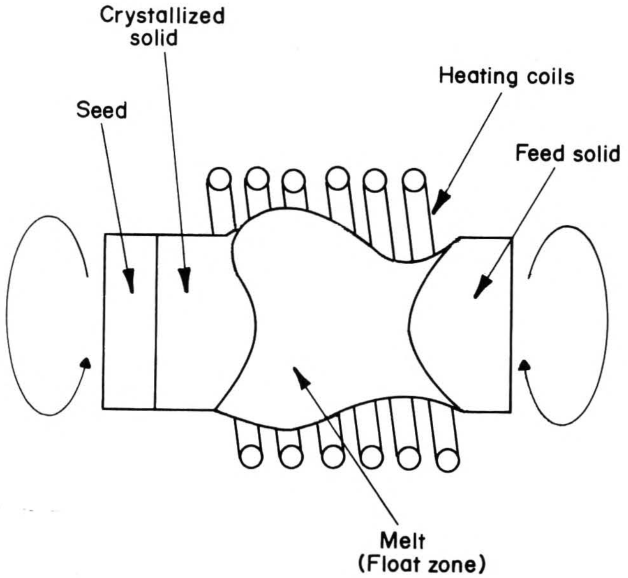

FIGURE 4. Float zone crystallization: a semicontainerless unit operation.

confined to microgravity environments, However, in one-g the resistive heat generated by the ionic current causes convective flow fields that can significantly degrade the quality of an electrophoretic separation. The sedimentation of cells can also degrade the separation. Since microgravity can eliminate some of these problems, electrophoretic separations in space have been actively investigated since the flights of Apollo 14 and Apollo 16. Most recently, McDonnell Douglas Astronautics Corporation has used continuous flow electrophoresis on board the space shuttle to separate biological model materials [14]. Chemical engineers are actively involved in modeling this complex phenomenon [15, 16].

Another type of unit operation which takes advantage of reduced sedimentation is exemplified by a proposed method for growing zeolites in microgravity [17]. When zeolites are formed in solution, their size is controlled by nucleation rates and the rate at which crystals sediment out of solution. In microgravity, the crystals can grow to a much larger size before they sediment, and nucleation rates may be reduced. This process is representative of a large class of processes that rely on solutions remaining homogeneous in microgravity.

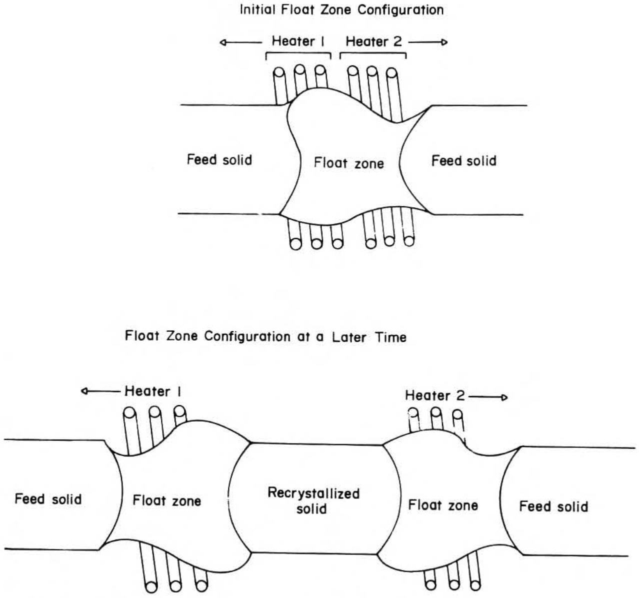

FIGURE 5. A new approach to float zone crystallization.

To this point, we have considered only unit operations that exploit microgravity. While microgravity can be beneficial, it can also cause difficulties in performing operations that are quite easily done at one-g. As an example, consider some of the unit operations required for optimizing the spacecraft ecosystem. In a long spaceflight there is strong motivation to use biological reactors to convert CO_2 to O_2 in order to reduce the amount of oxygen required for life support. In one-g reasonable rates of mass transfer can be obtained in biological reactors by bubbling gases through the reactor. In microgravity, bubbles do not rise due to buoyancy. However, it may be possible to immobilize cells on microcarriers and then obtain reasonable rates of mass transfer through agitation. But, agitation may result in cell damage. This unit operation is still under active development by chemical engineers collaborating with NASA [18].

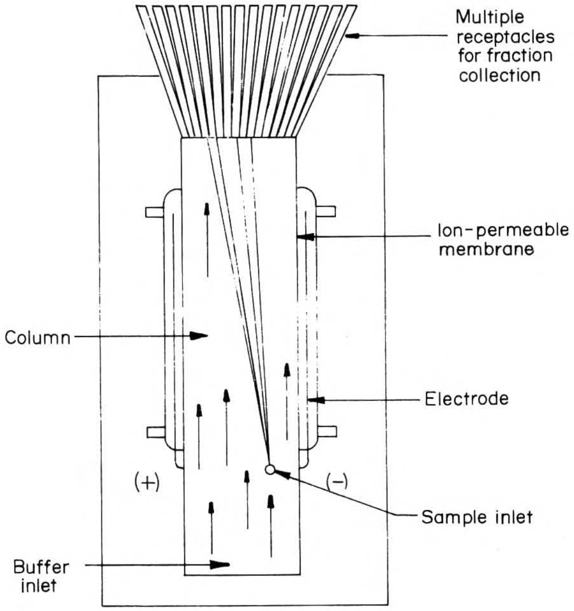

FIGURE 6. Electrophoretic separation.

CONCLUSION

This paper has enthusiastically reviewed a few of the many opportunities available for materials processing in space. This enthusiasm must be tempered, however, by the enormous costs associated with transporting material into space. These costs have been estimated to be several thousand dollars per pound. With these transportation costs, the value added by microgravity processing must approach that of turning lead into gold. While the value of some pharmaceuticals may justify manufacturing processes based on microgravity alchemy, in general the costs of microgravity processes must be justified by our improved understanding of the role of gravity in earth-based processes. So, although no great economic incentive exists to build manufacturing processes in space, unit operations in microgravity will continue to be developed. Opportunities exist for chemical en-

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plains the methodology of process control. This chapter bears some similarity to Chapter Three, but is much more thorough and useful.

The last section (Part III) is concerned with data bases and contains Chapter Twelve. It is one of the more useful chapters in the book as it describes the importance to the designer of having data banks available containing the physical properties in both the solid and molten phases of each thermoplastic. This data should be readily available in both the part design and process simulation phases and must be stored in the computer system. The chapter contains an overview of the development of the present data bases, including the types of data available in present systems and future trends.

In summary, there are a number of useful chapters in the book, but unfortunately the connection between chapters is not readily apparent. For the inexperienced engineer, it would be difficult to assemble the appropriate knowledge from this book and then apply it to process control or mold design. The book would be more useful if a section on principles of injection molding, including the fluid mechanics of mold filling and its connection to the properties of a part, were included at the beginning of the book. ☐

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pleted these courses they will know what to look for when they encounter new problems, and they will have acquired the tools necessary to solve a great many of them.

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gineers to develop entirely new processes, to understand current unit operations more thoroughly, or to adapt earth-based unit operations for the demanding environment of space.

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