

Materials processing in space — A brief review

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1. Introduction

This lecture presents a brief review of Materials Processing in Space. It is meant for the participants of this workshop, to get a flavour of what is being done and what is being planned in this field. Much of the information presented in this talk is derived from published literature (See references at the end of article). Detailed lectures on many of these topics will be given by later speakers.

Environmental parameters which affect materials processing are : (1) gravity ; (2) temperature ; and (3) pressure. Temperature and pressure can be controlled under laboratory conditions, but this is not so with gravity. Conditions in space differ in several important aspects from those obtaining on earth. The magnitude of gravity in space is nearly zero. There is unlimited vacuum pumping capacity. Contamination is comparatively low although the solar and cosmic radiations are not attenuated. Space has the capacity to behave as a "black body" heat sink. All these properties can be exploited for materials processing in space.

2. Achieving micro-gravity conditions

The earliest attempts to "neutralise" gravity was in the *Plateau tank*. In this tank there are two immiscible liquids having identical densities—one freely floating in the other. This tank does not really simulate zero g conditions. In it the body forces on the floating liquid are balanced out. This tank, apart from being a fascinating toy, has been used for many significant experiments.

Under free fall conditions the inertial forces balance out the gravitational forces so that the net gravitational force is zero. Unfortunately, ideal free fall conditions are difficult to attain due to many reasons—the presence of atmospheric drag, of centripetal forces, of vibrations, etc.

Near zero g conditions can be simulated on earth by dropping an experimental chamber in a tower, but micro-gravity conditions exist only for a few seconds. In the NASA Louis Research Centre there is a *drop tower* with a free fall distance of 130 metres in which the pressure is held at 10^{-2} torr to reduce drag and one can obtain 10^{-5} g for about 5.1 seconds.

Under "ballistic" flying conditions in an aircraft one can also attain near zero g conditions for a fraction of a minute. An experienced pilot can keep an experimental chamber floating in the aircraft by maintaining a specific "parabolic" trajectory.

Materials processing experiments can also be done in rocket flights under micro-gravity conditions for a few minutes. The European Space Agency and the Swedish Space Research Organisation have mounted detailed programmes of materials processing using rocket flights. This is of immediate interest to Indian Materials Scientists.

A satellite is continuously under free fall conditions. Even in this the value of g is not exactly equal to zero. This is primarily due to residual atmospheric drag, and also due to the reaction felt by the spacecraft due to thrust, vibrations etc. In the case of the *Spacelab* the residual accelerations can also be due to human or equipment movement and to the drift of suspended samples not in the line of the orbit of the centre of mass of the spacecraft.

When using a satellite, the recovery of the payload presents many problems. For this reason, the space shuttle programme of the United States is of considerable interest to materials scientists.

3. Convection due to gravity and surface tension

Perhaps the most important reason why there is so much excitement about processing of materials in space is because convection is considerably reduced under micro-gravity conditions. Convection currents are caused by acceleration forces acting on density differences. Convection cannot exist if the net acceleration is zero. Convection is sometimes, but not always, harmful in the processing of materials. When convection is considered deleterious in any process there would be an advantage in carrying it out in space.

Density gradients are produced by temperature gradients or concentration gradients. The small g values shown in table 1 are capable of driving convection currents. To find out the nature of convection movements, the velocity of the particles of the substance must be computed. Convection would be turbulent, if the velocity is large and laminar, if the velocity is small.

Table 1. Acceleration values in a low altitude earth orbiting satellite.

Atmosphere drag	$5 \times 10^{-5} g$
Centripetal force	$1 \times 10^{-6} g$
Gravity gradient	$3 \times 10^{-9} g$
Venting thrust	$10^{-4} g$ to $10^{-6} g$
Vehicle thrust	$10^{-2} g$ to $8 g$
Passive thermal control	$3 \times 10^{-6} g$
g jitter due to manoeuvres and vibrations	$10^{-3} g$

The phenomenon of convection can be described in terms of dimensionless parameters. The Grashof number (Gr) is a measure of the relative magnitudes of buoyancy and viscous forces. It is defined as

$$Gr = g \frac{d^3}{\nu^2} \Delta\rho/\rho$$

where g is the acceleration due to gravity, $\Delta\rho$ is the difference in density, ρ the reference density, ν the kinematic viscosity ($\nu = \mu/\rho$ where μ is the absolute viscosity) and d is a linear dimension. The Grashof number can also be written in terms of the temperature gradient or concentration gradient.

The condition for unstable convection is determined by the Rayleigh number which is related to the Grashof number by the equation

$$R_a = P_r \times Gr = C_p (\mu/k) Gr$$

where P_r is the Prandtl number, C_p the specific heat at constant pressure, μ the absolute viscosity and k the coefficient of thermal conductivity. A reduction in g results in a decrease in the value of Gr , and hence in the particle velocity and R_a . The effect of a low gravity environment is, therefore, to reduce convection effects. At 1 g the convection is turbulent and at 10^{-3} g gravity driven convection is laminar (figure 1).

Surface tension forces can also drive convection. The Bond number B_0 compares the gravity force with the surface tension force

$$B_0 = \rho g d^2/\sigma.$$

When g is large (as on the surface of the earth) surface tension forces are prominent only when the linear dimension (d) is very small. Under micro-gravity condition surface tension forces can take over even for large dimensions (figure 2a).

Not only surface tension but surface tension gradients can generate conventional convection flows or unstable cellular flows (just as gravity induces such flows) and these are known as the Marangoni effects. Surface tension forces can be affected by temperature and concentration gradients (see figure 2). Under micro-gravity conditions, surface tension forces can play an important role in convection phenomena. Convection affects not only the transport of the material but also the heat transfer characteristics of the system and both these are important in the processing of materials in space.

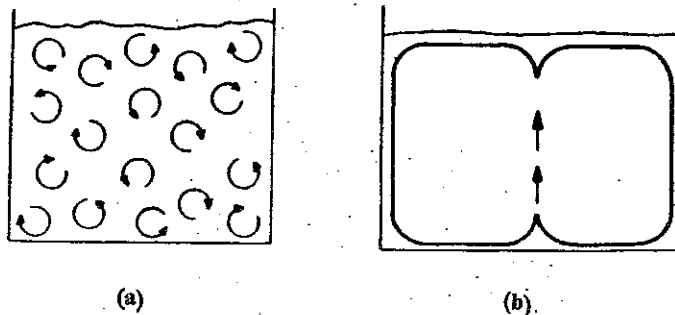


Figure 1. Gravity driven convection.

(a) 1 g : Turbulent ; (b) 10^{-3} g : laminar.

4. Some direct effects of gravity

There is no measurable influence of gravity on a rigid body, but there are small effects on high density materials which are soft. On the other hand, liquids and gases are strongly influenced by gravitational forces. Since solid materials are produced from liquid and gaseous phases, zero gravity conditions affect the production of materials considerably.

- At 1 g, a liquid is pressed into an open container, whereas at 0 g the liquid takes the shape of a sphere and floats freely (figure 3a).
- If a liquid contains solid particles then at 1 g they will float or sink depending on whether their density is smaller or larger than that of the liquid. After stirring segregation will take place in a few seconds. In 0 g conditions there will be no gravity induced segregation (figure 3c).
- The effect of gravity on two immiscible liquids with different densities is for the lighter one to float on top of the heavier one. In space, this will not be the case. One liquid would break up into spherical droplets which float freely in the other (figure 3b). An oil water-emulsion segregates in 0.1 sec when $g = 1$ but it is stable for about 10 hours under micro-gravity conditions (*i.e.*, it is at least 10^5 times more stable).

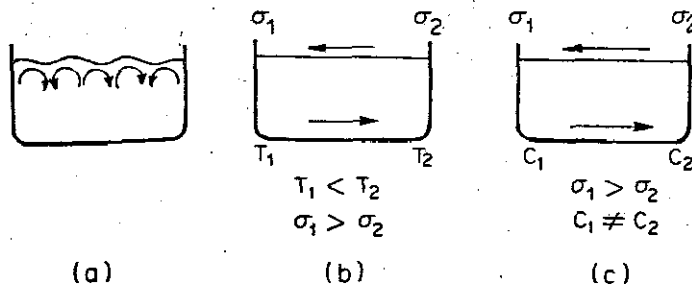


Figure 2. Surface tension driven convection (a) turbulent at $10^{-6}g$; Marangoni convection due to surface tension being dependent upon (b) temperature and (c) concentration of the solute.

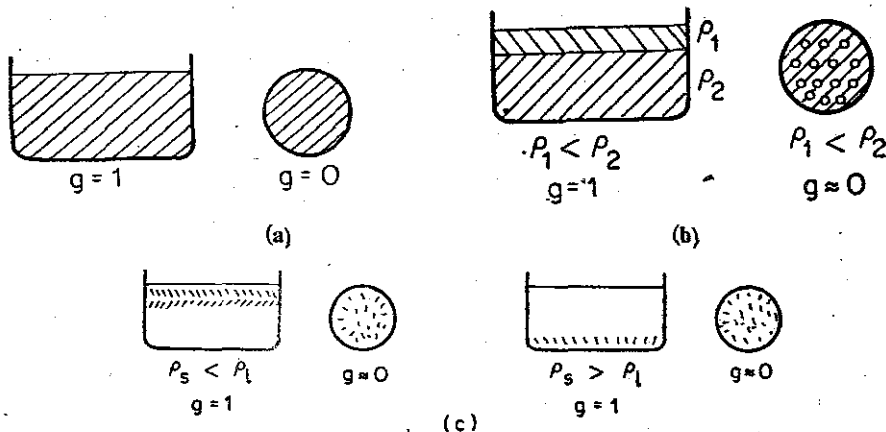


Figure 3. The effect of gravity on liquid systems.
 (a) Single liquid; (b) Two liquids; (c) Solid in liquid.

- (d) In a liquid-gas system, in zero g conditions the bubbles will not segregate so that by solidifying the liquid it would be possible to produce uniform foams.

5. Positioning and other devices

Only when g is exactly equal to zero will a solid or liquid not 'fall'. In microgravity conditions, which are only normally attainable, particles will fall through distances which although small are not negligible. The movement when gravity is $10^{-5}g$ is 0.005 cm per second and 50 cm in 100 seconds.

It is, therefore, necessary to have devices which keep solids and liquids stationary in microgravity conditions. Since only weak forces are necessary to move these particles in space, very elegant electrostatic and acoustic positioning devices have been designed for this purpose. For example, with ultrasonic standing waves using only one transducer it is possible to achieve multiaxial positioning. The system becomes quite complex if the object is to be held stationary in a tube furnace with changing temperatures.

In many experiments one of the components, a solid or a liquid has to be mixed or dispersed in another. Ultrasonic and electromagnetic stirring devices have been made for this purpose (for dispersing, emulsifying and homogenising).

6. Furnaces in space

A fair amount of thought has gone into the question of designing furnaces for materials science experiments in space. High frequency heaters and furnaces cannot be used in space because of their bulk, low efficiency and electromagnetic interference. The main features of any furnace should be lightness and with minimum power requirements again to cut down weight on power sources. The furnace should therefore have high efficiency. For experiments in space it is preferable to design multipurpose facilities as different experiments can be conducted with the same equipment. Furnaces which are intended for use in the Spacelab can be reused in subsequent missions and the range of facilities can be increased or improved upon as time goes on.

An isothermal furnace to reach 2400°C has been designed and fabricated. It can operate under vacuum or inert gas conditions. Special multifoil insulation (consisting of many layers of thin metal foil coated with ZrO_2) which reduces heat losses very considerably, is used. The furnace has a very rapid heating up time (1000°C in 90 seconds with a 1000 W input): A power of 200 W is necessary to maintain a constant temperature of 1000°C . Cooling rates of $250^{\circ}\text{C}/\text{min}$ can be achieved using a helium gas flow. The working space is 70 mm in diameter and 90 mm long. The furnace has quick coupling locks through which various devices can be introduced. The material can be placed in cartridges or levitated and positioned by ultrasonic acoustic wave pressure mentioned earlier.

The isothermal heating facility can be used for solidification studies, for basic diffusion experiments, casting of metals and composites, preparation of glasses and ceramics.

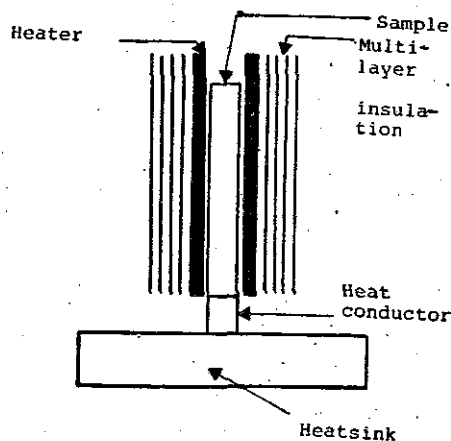


Figure 4. Principle of gradient furnace used in rocket experiments useful for directional solidification. A well-defined temperature gradient is achieved by the extracting heat sink at one end of the furnace. Multilayer insulation is used to minimise transverse heat flow.

A gradient heating facility for low and high temperatures is necessary for many crystal growth and zone refining experiments. The thermal gradient can be produced by extracting heat using a heat sink (figure 4). A furnace with three independent heating elements has also been designed so that a multitude of temperature profiles can be obtained. These furnaces are capable of isothermal and gradient modes. Here again the multifoil insulation is used. The temperature gradient can be up to $150^{\circ}\text{C}/\text{cm}$ and the maximum temperature is limited to 1200°C . Both inert gas atmosphere or a "vacuum environment" are possible.

Mirror heating furnaces have also been designed and fabricated. Two types have been made with heating elements consisting of one or two tungsten-iodine lamps. In the former, the lamp (800 W) would be at one focus of an ellipsoidal gold plated quartz mirror and the specimen is at the other focus. In the two lamp version (figure 5) the mirror consists of two intersecting ellipsoidal cavities with the sample located at the common focus and the lamps on either side of the specimen at the two other foci. One can attain $2000\text{--}2200^{\circ}\text{C}$ so that an alumina rod can be melted over a volume of 1 cc. It is advantageous to enclose the material in a quartz tube filled with inert gas to reduce evaporation of the melt. Suitable pulling mechanism with appropriate rotating feeds are provided, pulling speeds varying from 10^{-5} to 50 mm/min being attainable.

It would be a great advantage if solar furnaces are constructed for space use. This would remove the limitations put on capabilities of furnaces due to the electrical energy available from batteries and fuel cells in spacecraft. The use of solar furnaces would involve the orientation of the spacecraft and the mirror. It would be ideal if the solar furnaces could be combined with the ultra high vacuum of the molecular shield described in the next section, although the orienting the equipment will become rather complicated.

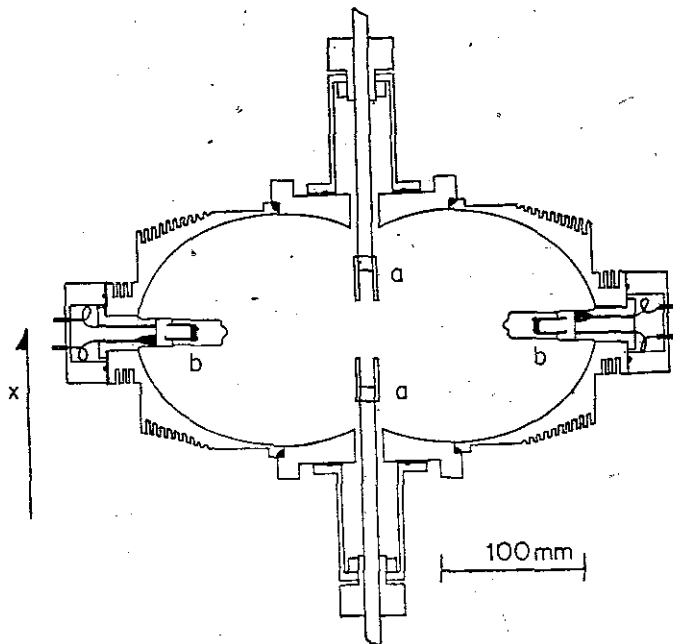


Figure 5. The double ellipsoidal mirror furnace. The furnace cavity has a polished gold plated surface. (a) The sample at the common focus (only the crystal holder is shown); (b) Tungsten-halogen lamps are at the other foci of the ellipsoids.

7. Ultra-high vacuum—The molecular shield

A novel idea has been put forward for producing ultra-high vacuum over a large volume at altitudes of 200 to 300 km. The atmosphere at these heights has a composition very different from that near the surface of the earth. The ultra-violet radiation from the sun dissociates the gases (particularly oxygen and water). The atmosphere, therefore, consists mainly of atomic oxygen, atomic hydrogen and helium. While objects at these heights can be very cold when the sun is not shining on them, the "temperature" of the atmosphere itself can be as high as 800°K to 1000°K . At these heights the number of atoms per cc is between 10^8 and 10^{10} while near the surface of the earth it is about $10^{19}/\text{cc}$. In spite of these low pressures, these reactive atoms can act as a source of impurity, particularly if one is interested in preparing ultra-pure substances. To overcome this problem a suggestion of using a hemispherical shield 3 to 10 m diameter pulled by a space vehicle (or orbited in space) has been made (figure 6). The shield will move at a velocity of 8 km/sec and the convex front surface will sweep out the molecules in front. The molecules cannot come behind the shield as the mean free path of the molecules at these heights is about 0.4 km which is very much greater than the shield dimensions. In fact the collision with the shield will be the last collision which the molecules will suffer. The experimental region is the hollow or the concave side of the hemisphere. The sources which contribute to the density inside the shield are (1) the free stream atmosphere, (2) outgassing of the inner side of the shield, (3) the gas released by the experiment, (4) the gas scattered

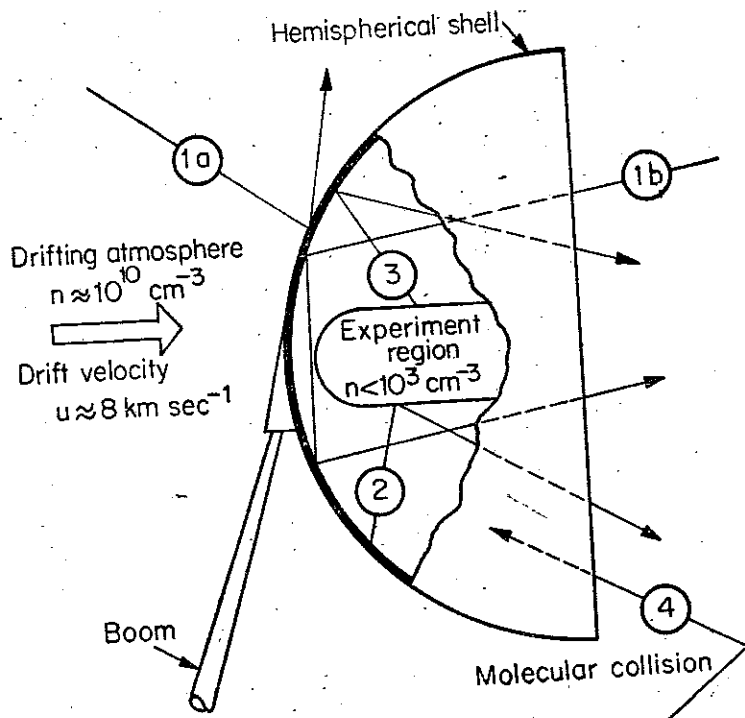


Figure 6. The molecular shield for experiments at ultra-high vacuum in space. The drift velocity of the shield is 8 km/sec. The surrounding atmosphere has 10^{10} atoms/cc. While the experimental region on the concave side has only 10^3 atoms/cc.

by the space vehicle (the orbiter) which pulls the shield, and the gas released by the orbiter itself (outgassing leaks, vents, etc.) (see figure 6). The effect of each of these can approximately be calculated if one assumes a drifting Maxwellian gas and that molecules on colliding with the inner surface of the shield are first absorbed, then thermally "accommodated" and finally remitted. A detailed calculation shows that the *maximum number of atoms within the shield will be 10^3 /cc* when the number of atoms in the atmosphere surrounding the shield is between 10^8 and 10^{10} . Strangely enough most of these 10^3 atoms/cc are due to the degassing of the shield itself!

If materials are to be processed in the ultra-high vacuum of the shield we must incorporate various devices like furnaces (resistive, mirror and solar), crystal-pullers, positioning devices into the molecular shield.

8. Crystal growth

When semiconductor crystals are grown in the absence of gravity-induced convection they are expected to have a degree of perfection and chemical homogeneity not otherwise obtainable.

It is the dream of semiconductor physicists to grow long, large diameter defect-free crystals. Defects cause malfunctioning of devices, rapid ageing, low reliability and low yields in manufacture. In the case of silicon, large diameter crystals are of advantage in making high current devices, as the current density can be kept low. Further, if the diameter becomes larger, the number of single devices required for any application will be smaller. In making integrated circuits the handling cost per chip will be lower if the wafer is large. The yield also increases with diameter of the wafer as most of the imperfections will be on the periphery. For growing good, large crystals, the crucible-free float-zone-refining technique seems to be the best. This consists of moving a molten zone along the length of a polycrystalline rod or a single crystal rod. The purification takes place because of the greater solubility of the impurities in the liquid than in the solid. Under 1 g condition only those substances with a large ratio of surface tension to density can be float-zone-refined because the liquid is held up between the two solid pieces by surface tension forces.

Under micro-gravity condition, in theory at least, all substances can be float-zone-refined. Under 1 g condition, diffusion and gravity-driven convection mixing predominate while in micro-gravity environment the diffusion and surface tension becomes important. Because of this the transport of heat becomes slower affecting the growth rate. Hence a large number of experiments have to be devised to understand many of these phenomena.

Free floating specimens (made stationary with acoustical or electrostatic positioning devices) can be used to study the properties of high temperature melts (with no reaction with the container material). Influence of surface tension on nucleation, crystallisation can also be studied and this would generate important data for the understanding of many phenomena connected with crystallisation. For example, it is well-known that a concave solid/liquid interface is necessary to avoid faceting when silicon crystals are grown but the exact reasons are not understood. The nature of convection current, the effect of the shape of the solid/liquid interface, the influence of surface tension and electrodynamic forces can be elucidated by space experiments.

Sometimes, it is important to estimate the strength of the Marangoni convection and its effect on crystal growth. For studying this it is not always necessary to do experiments in space. One could use the Plateau tank in which a silicon sphere is immersed in an inert oxygen-free fluorite melt having the same density.

Binary crystals whose composition ratios depend on vapour pressure have to be grown under very high pressures. This difficulty has been overcome in the travelling heater method. The liquid zone between the seed crystal and feed rod is not the melt of the crystal but of the solution of the crystal in a solvent. Indium antimonide (InSb) from a polycrystalline feed dissolves in indium which has a low melting point. The solute is transported from the feed rod through the solvent to the seed crystal by diffusion (figure 7). Because of this the rate of growth is low—a few mm per day. However, this method has many advantages such as the reduction of lattice defects as the temperature is low, control of the stoichiometry, the reduction of foreign atoms, the reaction with walls of the crucible is smaller. Further, as the surface tension is higher at lower temperatures this

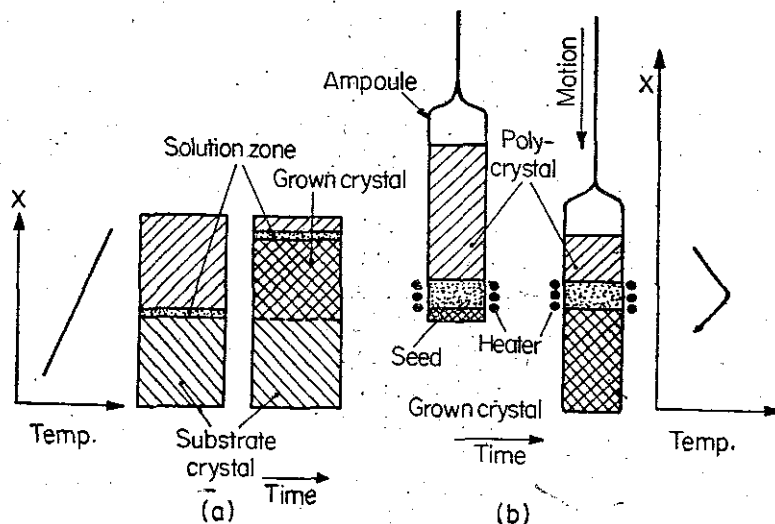


Figure 7. Schematic diagrams of (a) the travelling solvent methods and (b) the travelling heater method for growing binary crystals.

is better amenable to crucible free-zone melting. Experiments in space may throw light in understanding many aspects of this process.

Many crystal growth experiments are being planned in space. A few are listed below:

The influence of convection and the Marangoni effect on the formation of striations (dopant inhomogeneities) in silicon single crystals.

To differentiate the influence of diffusion and convection on crystal growth with controlled dopant distribution.

To grow crystals with various organic charge transfer complexes (like TTF-TCNQ) which show quasi one-dimensional conductivity and which will be grown from solution by the diffusion processes. Highest crystal perfection, which appears to be the prerequisite for high conductivity at 60°K , may be attained in space.

The diffusion growth of large single crystals of proteins like 2β Haemoglobin (molecular weight 32,000) and β -Galactosidase (molecular weight 520,000). Such large single crystals are necessary for the x-ray and neutron structure analysis.

9. The fluid physics module

In the float-zone technique one must know whether a liquid drop of the material can be supported between two rotating rods—a condition essential for this method to operate. This experiment has actually been done in space using silicon and the basic feasibility of the float-zone technique in space environment has been established (figure 8). However, several phenomena connected with the hydrodynamics of floating liquid zones have to be studied. The hydrodynamicist must now consider some rather important questions, like drop dynamics, shaping and degassing of liquefied substances, boundary layers and their properties, capillary

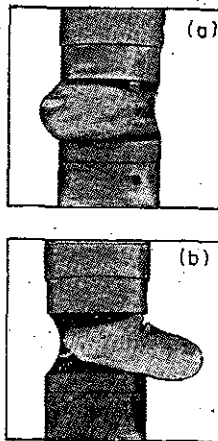


Figure 8. Distortion of liquid zone in the float zone technique.

forces and stability, the fluid dynamics and heat transfer in the floating-zone under micro-gravity conditions.

A rather sophisticated apparatus called the "Fluid Physics Module" has been designed which allows the study of static and dynamic characteristics of fluids by spinning, oscillating or vibrating a liquid zone. The data is recorded on film when the experiment is conducted in the space shuttle and evaluated on earth when the payload is recovered.

Another investigation is the study of *adhesion* between phases (liquid/solid) in the absence of electric and magnetic forces. In many capillary systems the work of adhesion is opposed by the work of cohesion of the liquid so that the spreading and non-spreading situations are dependent on which of the two forces is greater. Since the van der Waals forces involved in this, fall off very rapidly with distance, it is not possible to study these in terrestrial experiments as the gravitational forces mask all attempts to study these forces in microscopic systems. In the fluid physics module the properties of the liquid bridge zone between two solid discs will be studied. From the shape of the liquid bridge, the interaction forces will be derived so that critical distances at which instabilities occur will be determined (see figure 8).

The kinetics of the spreading of liquids on solids will be studied. In micro-gravity it would be possible to study large systems in which the curvature effects are small and the fluid flow is predominantly driven by movements of the contact line.

Another experiment intends to study the unsolved classical problem in analytical mechanics of coupled motion of liquid-solid systems.

10. Liquid phase miscibility gap

The liquid phase miscibility gap is a well-known phenomenon in which single liquid phase separates into two liquid phases of different composition when cooled

below a specific temperature. There are a large number of systems which are known to display this liquid phase miscibility gap. Al-Pb, Pb-Au, Bi-Ga, Au-Ga, Cu-Pb are some typical examples in the metallurgical field. To fix our ideas let us consider the Al-Pb system. Between 1.5% and 15% of Pb, a single liquid phase is formed at high temperatures. When cooled (1040° C for 15% Pb and 658.5° C for 1.5 Pb) two liquid phases separate out, lead drops form in an aluminium-rich liquid matrix. The particle formation may be due to (a) spinoidal decomposition in which case the phases form instantaneously, giving fine particles distributed homogeneously, (b) nucleation and growth, in which case coarser particles form.

Initially Pb is finely dispersed and uniformly distributed in the aluminium-rich matrix. However, lead (Pb), being very much denser, begins to sink due to gravity, the particles coalesce and segregation between the matrix and the dispersed phase takes place. The segregation is due to the well-known Stokes migration. Convection currents also make things more complicated. It is clear that under micro-gravity environment these effects can be minimised. In fact, if the temperature of the homogeneous suspension is lowered (under micro-gravity environment) one would get a solid with finely dispersed particles. Such systems have many practical uses.

If one can produce materials with a uniformly dispersed second phase, it would be the first step towards making many technically important materials. For example, Al-Pb with Pb uniformly dispersed would make better bearings. Zn-Pb system would make better electrodes for dry cells.

11. Eutectic alloys

In eutectic solidification, a single liquid phase when cooled forms two solid phases of different compositions. Using this phenomenon one can under proper

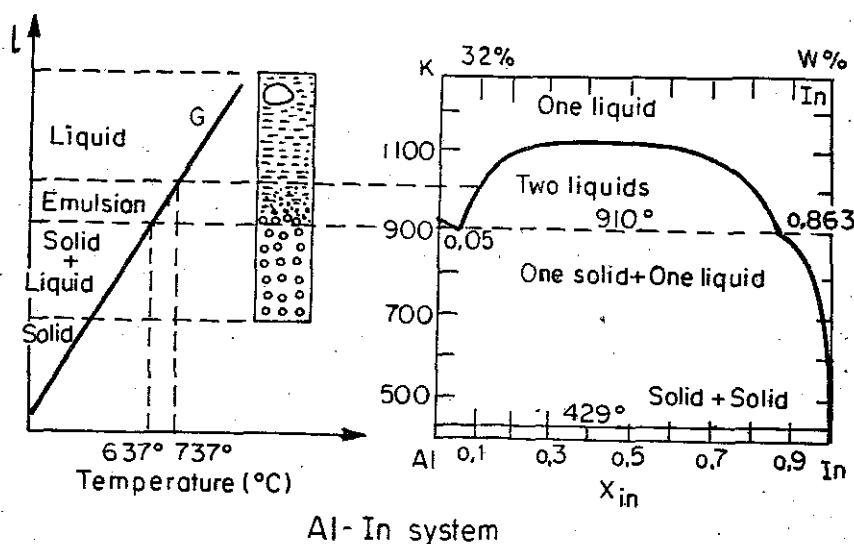


Figure 9. Phase diagram of aluminium-indium system and the formation of dispersed composites.

conditions (unidirectional solidification) produce a composite. These are *in situ* composites in contrast to other composites where the matrix and the reinforcing phases are produced independently and then mixed. When the two phases separate out in eutectic solidification the morphology of the two solids considerably differ. Lamella, fibres or irregular particles may be formed and further the phases may contain a large number of imperfections. When defect-free crystals are formed, the resulting solid is extremely strong. Unfortunately, the exact conditions of formation of a defect-free phase are not known. There is, therefore, a great deal of interest in discovering what these conditions are. One school believes that defects are caused mainly by convection movements and so an improvement in quality may be expected by processing these materials in space. Unless these experiments are planned carefully, it would be very difficult to interpret the results. Eutectic solidification is a very complex phenomenon, involving homogeneous and heterogeneous nucleation, heat and mass transport coupled with the growth of phases, equilibria of surface tension forces, etc. The exact eutectic composition of these alloys must be known as any deviation from this composition can quite adversely affect the solidification process. The eutectic compositions are usually known only to an accuracy of 5000 ppm. If the composition is not exact there would be supersaturation followed by the rejection of the solute. In gravity environment, convection currents set in at the immediate neighbourhood of the liquid-solid interface. However, in space where convection is minimal, this natural stabilising effect is not present, leading to the growth of dendrites. The number of parameters involved in this phenomenon is so large that planning an experiment in space for understanding it appears to be difficult. It is a pity that in this field most of the experiments undertaken so far relate to potential application and not to the understanding of this interesting but complex phenomenon.

NaF-NaCl eutectic has been crystallised in space. NaF fibres were more uniformly spaced and better aligned than those produced on earth. This eutectic is a potential fibre-optic material. Furthermore, the visible and infrared transmission was found to be better than those for the same material made in a 1 g environment.

12. Composites

The making of composite materials in space appears attractive. Most of the strong fibres like Al_2O_3 , SiC and C have densities lower than those of metallic matrix materials. Low gravity conditions appears to be of advantage for uniform distribution. Higher volume fractions and more complex geometries can also be attempted. Further, it may also be possible to incorporate the fibres with minimum mechanical damage. Unfortunately, in space the problem of particle and fibre agglomeration will become very serious. The clumping together of fibres cannot be broken up by stirring alone (see figures 10 and 11). These problems are connected with wettability, outgassing, etc. The question of the elimination of bubbles has also to be solved before any significant progress can be expected in this field.

Extremely sophisticated processes are being planned for space experimentation. For example, methods of improving turbine blades by growing them as equiaxed or even as single crystals are being thought of. One suggestion is to get by eutectic

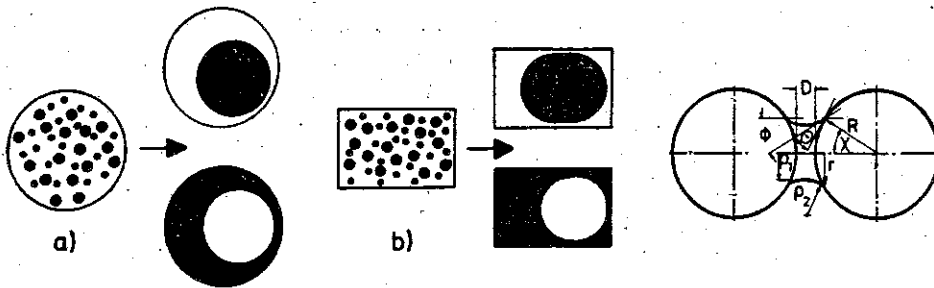


Figure 10. The effect of wetting behaviour on the dispersion of solid fiber in molten liquid metal-matrix in zero gravity conditions.

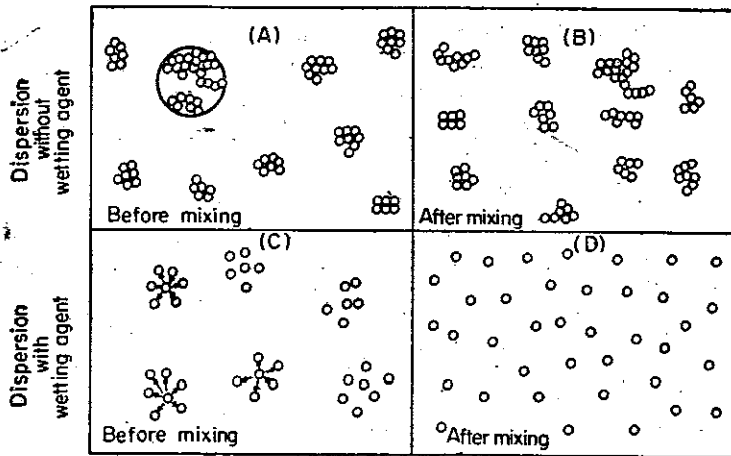


Figure 11. The effect of surface tension in the formation of two liquid phases.

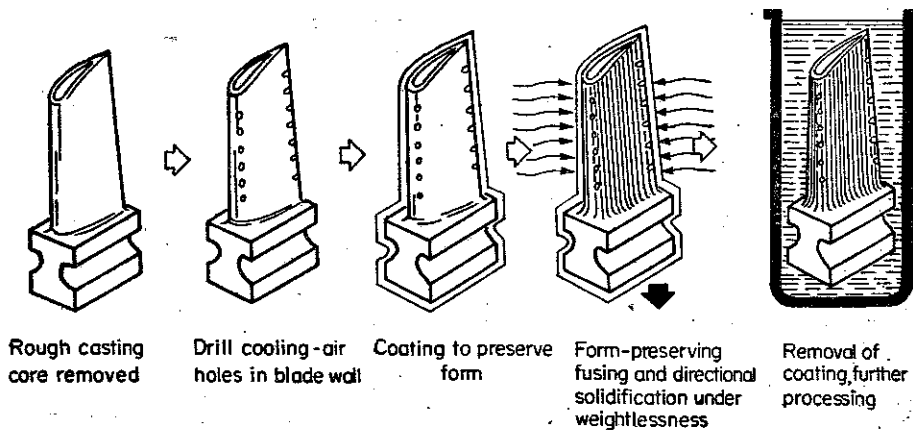


Figure 12. The steps in the manufacture of directionally solidified turbine blades strengthened by fibres formed from eutectic alloys. (1) Non-directionally solidified rough cast blade with the core removed, (2) Air holes for cooling drilled in the blade wall. (3) Plasma sprayed outer coating or skin which acts as the container of the material in the space. (4) Blade taken into space and under weightless conditions remelted in skin and directionally solidified so that oriented fibres Co Ta C are formed. (5) Blade brought back to the earth, coating removed and finished.

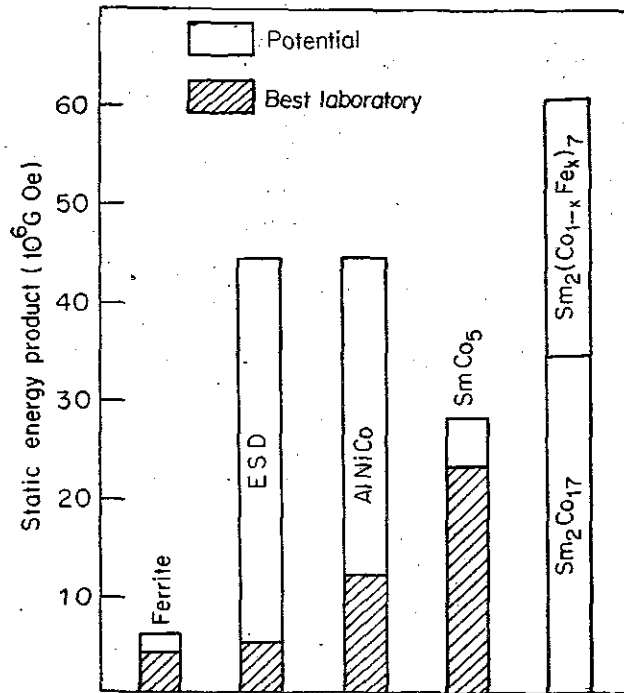


Figure 13. Improvements that are possible in the quality of magnetic materials if processed in space.

solidification, oriented fibres of CoTaC in the blades so that extra high temperature strength can be obtained and the blades used at temperatures 50° C to 100° C higher. But in these blades it would be necessary to drill holes for trailing edge convection cooling. But with fibres present electro-machining will be difficult. The process suggested is to make a blade using a eutectic alloy on earth, and remove the core; drill cooling air holes in the blade wall; give a thin coating or skin on the blade by plasma spraying, chemical vapour deposition or cementation. The blade is now taken to space, remelted in the skin, directionally solidified under weightlessness, brought back to earth, for the coating to be removed and for further processing.

13. Magnetic materials

Of some technical importance is the improvement of permanent magnets. The decrease of convection can make processing of such magnetic materials very efficient. For example, the elongated single domain magnets (ESD) make use of the shape and crystal anisotropy of single domain particles. These are prepared by electrolytic reduction. Convection induces side-branch dendrite growth making the single domain less effective and less efficient. In space a much better length to diameter ratio can be attained. Figure 13 gives the energy product value of some of the magnets, and the expected improvements if they are processed in space.

14. Electrophoresis

In biological research it is often necessary to separate pure samples of cells of a single specific type from a mixture of living cells. If the masses, the sizes or the shapes of the cells are different, we can, in theory, effect this separation. Those that differ in mass can be separated by sedimentation or centrifuging; those that differ in size by filtration through membranes having different pore sizes; and those that differ in shape by flow techniques. Living cells usually are fragile and centrifuging or filtration may destroy them. Further, many of these cells are so similar that they may not differ much in their masses, sizes and shapes.

An effective method used for the separation of such cells is by electrophoresis. This method uses the fact that (a) living cells have a surface charge, and (b) the quantity of this charge is as unique to each type of cell as its biological function. A mixture of different cells is placed in a glass vessel containing an electrolytic buffer solution whose composition, pH, etc., are compatible with the biological vitality of the cell. When an electric potential is applied, the cells would move and separate into zones depending on their electrophoretic mobility. In normal gravity environment, the density differences between the separated zones and the buffer solution often cause sedimentation. A more serious disturbing effect is caused by the Joule heating of the column, which induces destabilising convection currents. Under micro-gravity conditions these serious limitations can, in theory, be overcome.

A second method of separation is by flow electrophoresis in which the buffer solution is made to flow from left to right and the cell mixture is continuously fed into the flowing liquid. An electric field is applied perpendicular to the direction of flow so that the cells separate laterally in a fan-like manner and are collected through tiny vents.

A successful experiment done in space is the separation of cells that produce the enzyme urokinase which is produced in the foetal kidney cells and which can dissolve blood clots. Only 5% of the kidney cortex of the foetal kidney has this capability of producing urokinase and so a separation experiment is essential. The destabilising effects under normal gravity conditions are too large for effective separation and so an experiment was tried out in space. The material was first frozen to maintain the cell viability. The mixture was defrozen and processed electrophoretically in space. The columns were frozen again, stored, brought back to earth and analysed. The results were encouraging. This is the first of many exciting experiments that are to be done in space in the field of biology.

15. The space shuttle

The United States of America is planning a reusable facility called the space shuttle. When operational it would be possible to put a variety of payloads into orbit comparatively inexpensively. The space shuttle system consists of the orbiter, an external tank containing the ascent propellant, and two solid rocket boosters (SRB). The orbiter's main engines and two SRBs will fire in parallel at lift-off. The SRBs will be jettisoned after burn-out and can be recovered by a parachute system. After orbiting for a period the orbiter can "re-enter" the

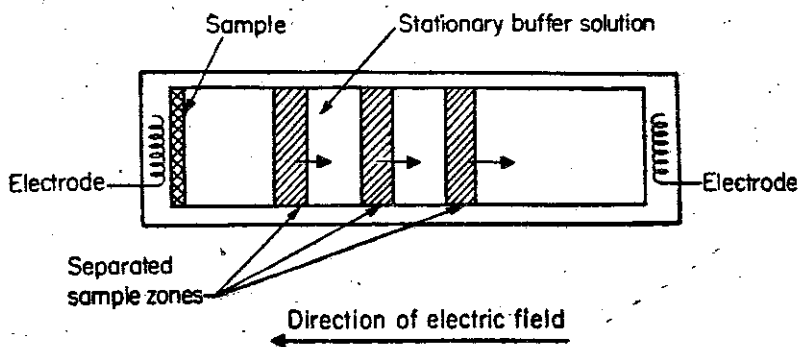


Figure 14. Diagram illustrating electrophoresis: Cells with differing surface charges move with different velocities and separate into zones. The sedimentation and also the convection currents set up due to the Joule heating under normal gravity conditions can be avoided if the experiment is carried out in space.

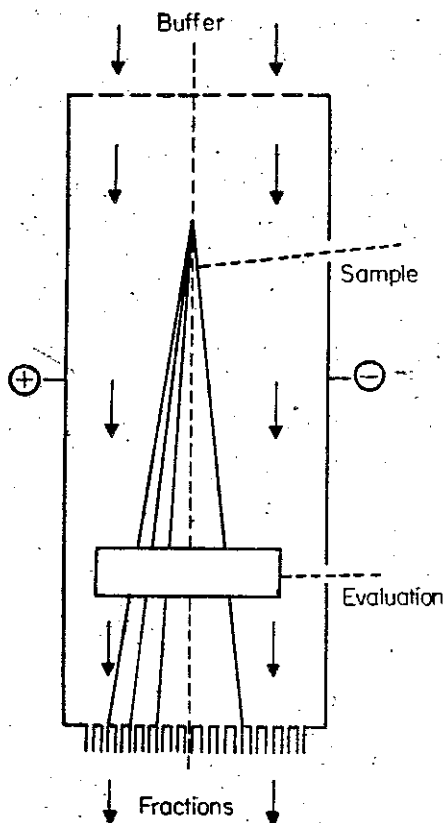


Figure 15. A second type of electrophoresis where the solution with the sample flows in one direction and the electric field is applied in the perpendicular direction.

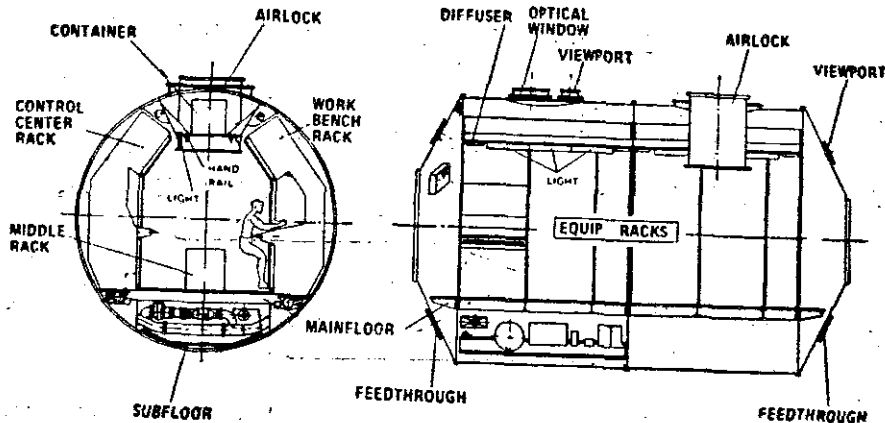


Figure 16. Cross-section of the Spacelab.

earth atmosphere and land on the earth in a manner similar to an aircraft. The nominal duration of a mission is 7 days but it can be extended to as long as 30 days.

The primary mission for the space shuttle is the delivery of payloads to earth orbit and can place payloads of 29,500 kg into orbit. The orbiter has the capability to retrieve payloads from orbit for reuse, to service or refurbish satellites in space, and what is most relevant to us, to operate laboratories in space. The space shuttle crew can actually perform experiments in space in what is termed as "shirt sleeve environment". The experimental sample and equipment can be brought back to earth at the end of the mission and used for post-flight analysis.

16. Sounding rockets

The experimental time available at $10^{-4}g$ as a function of payload weight for various rocket configurations vary from a few seconds to a few minutes.

The Texas sounding rockets experiment on materials science have been quite successful. Table 2 gives data of the payload in the Texas I and Texas II, programmes.

Table 2.

	Texas I	Texas II
Weight	347 kg	361 kg
Length	450 cm	450 cm
Start of "0" g	70 sec	72 sec
End of "0" g	445 sec.	453 sec.
Duration	375 sec.	381 sec.
Apogee	265 km	264 km

The Texus payloads had isothermal and multipurpose furnaces with acoustic levitation, a fluid cell, electrolysis cell, etc.

17. Possible Indian Experiments

India has a definite space programme. It seems quite appropriate for her scientists to give some thought to planning experiments in space and also on the space shuttle. There have been requests to the countries of the world for proposals for performing experiments in space using the space shuttle.

We have to give serious thought to the types of experiments that India could perform in space in the field of materials and their processing. As examples, I shall name two experiments which come to my mind. These are related to the research work done in Bangalore. We have been preparing a class of substances called electrocomposites. A powder which may be a ceramic, a plastic or a conducting material is suspended in an electrolytic solution in a bath. When the metal is electrodeposited on a substrate the powder also gets codeposited! The material produced in this manner may be stronger, more wear-resistant, more corrosion-resistant, or having better lubricating properties than the metal itself. In fact, the properties can be controlled by varying the nature of the suspended powder, or the conditions of electroplating. The exact mechanism of codeposition has not yet been fully understood. Further, it is not clear why comparatively larger particles, those greater than 1 micron can increase the strength of a metal by 75% to 120%. Producing these electrocomposites in space would ensure a very uniform distribution of the particulate matter in the electrolyte and hence in the composite. If experiments in space are planned properly, one may possibly get an insight into the mechanisms of deposition and strengthening.

Scientists in Bangalore are also interested in the variation of the surface tension of a liquid crystal with direction. Unfortunately, the exact measurement of this directionally dependent surface tension is made difficult by the distorting effect of the weight of the liquid crystal drop itself. This would be an ideal experiment to perform in space. This would involve forming a drop of a "single crystal" of a liquid crystal, photographing it from different directions and measuring the curvature of each face and computing the surface tension. There are many such experiments which may be worth performing.

18. Value of materials science experiments in space

A great deal of thinking is going on about the nature of scientific and technological experiments that are to be done in space. There are discussions as to whether experiments should be technologically oriented, whether appreciable quantities of materials should be processed in space or whether these experiments should be oriented towards the understanding of phenomena which will progress the field of materials science.

In the early enthusiastic phase, a greater stress was laid on technology and even production. In fact plans were afoot to deploy ten large cylindrical molecular shields (18 m × 9.6 m) of the free flying type to produce 5×10^6 square metres

of silicon for solar cells. It was estimated that the cost of production in space may be lower than that on earth. Similarly it is stated that producing space turbine blades for aircraft would be approximately the same as the present-day cost on earth. To many it seems quite unrealistic to process and produce components regularly in space.

The view that experiments performed in space would lead to better understanding of the science, so that processes on earth could be improved is gaining ground. Such experiments may help to make crystal growing more of a science. Further it is felt that specific experiments which cannot be done on earth should be done in space. For example, the study of the self-diffusion of zinc in liquid zinc using ^{65}Zn isotope (figure 17) is considered a classic experiment that has been done in space and it could not have been done on earth. The surface tension experiments in liquid crystals suggested earlier comes under this category. Can we understand more about the van der Waal's forces, critical point phenomena, the nature of impact, adhesion or friction by performing experiments in space?

Since space research is expensive a great deal of thought has to go into the designing of experiments. Many of these experiments have to be critically discussed by a large number of scientists, thus inculcating a greater sense of co-operation amongst scientists nationally and internationally. This itself seems to be worthwhile. If as much of thought goes into designing, earth bound experiments as that given to space experiments the results can be spectacular.

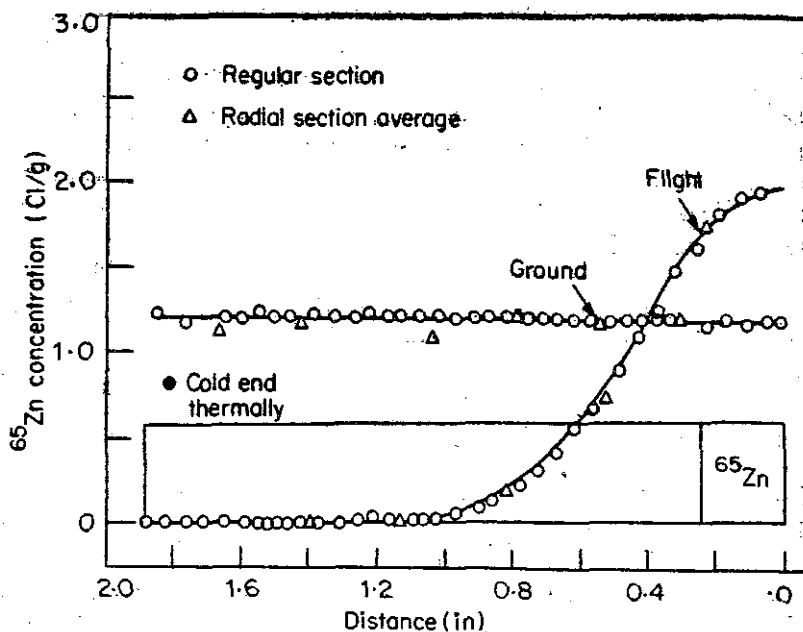


Figure 17. Self-diffusion coefficient of liquid zinc determined using radioactive ^{65}Zn isotope (Skylab experiment). There is close agreement between theory and experiment. The values obtained on earth are very different because of the interfering convective processes.

It has been calculated that the spin offs of space research are also not negligible. For example, it is estimated that if all the furnaces on earth were as well insulated as those going into the Spacelab, the saving in electricity costs alone would go a long way to financing the Spacelab programme!

There are supporters and detractors. The main arguments are : Earth-based experience is sometimes not enough for reliable forecast of behaviour in gravity-free environment. Further, in most space experiments the results are not yet completely understood.

To me the main argument for space experimentation is the following : History has time and again showed that once an initial breakthrough is made, it is somehow much easier to achieve the same result by another route.

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