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Solar Furnace Satellite for Large Diameter Crystal Growth in Space

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Crystal growth research over the last 15 years indicates that much of the inability of crystal growers to reach the theoretical limits of perfection in their crystals is due to gravity induced convection. Investigators worldwide are preparing experiments to test the influence of low gravity found in space on the growth of many crystalline materials. However, power limitations prevent existing space crystal growth furnaces from being able to process samples any larger than about 2 cm, and in addition, the background microgravity levels found on the Space Shuttle are not low enough to significantly benefit samples much larger than 2 cm. This paper describes a novel concept of a free-flying platform utilizing well-established solar furnace technology to enable materials processing in space experiments on large-diameter crystals. The conceptual design of this Solar Furnace Satellite is described along with its operational scenario and the anticipated *g* levels.

Nomenclature

A_{p1}	= projected area perpendicular to the velocity vector
A_{p2}	= projected area normal to incoming solar radiation
C_d	= drag coefficient, $2 < C_d < 3.5$ for most spacecraft
g level	= effective acceleration acting on a space payload, 9.81 m s^{-2} on Earth
h	= altitude
M	= total spacecraft mass
P_{sr}	= solar radiation pressure, 9.33×10^{-6} Pa for a perfectly reflecting body
R_e	= mean radius of the Earth
V_s	= equilibrium orbital velocity of the spacecraft
μ	= gravitational parameter of the Earth, 3.98×10^{14} m^2 s^{-2}
ρ	= atmospheric density
ω	= orbital rate, rad/s

Introduction

CRYSTAL growth research in space offers industry the opportunity to significantly minimize the driving force for buoyancy convection, eliminate hydrostatic stresses, and grow benchmark crystals if power limitations can be overcome.[1] Early research results indicate that these benchmark crystals may be free of significant compositional segregation, impurities, and defects if the gravity levels are below about 10^6 g (Ref. 2). The crystals and the techniques for producing them in space may spur similar improvements in Earth-based crystal growth technologies. For example, the application of advanced computational fluid dynamics to the design of space-based systems is expected to enable the development of new design tools and methodologies that can be directly applied to Earth-based systems. In fact, systematic investigation of the physical behavior of large-diameter crystal growth systems in space may catalyze the development of the Earth-based technologies required to approximate the space-based results.

The most important consequence of convection in directional solidification/crystal growth is the segregation of the various chemical species in the melt and the resultant nonuniform distribution in the final product. For semiconductor applications, extreme compositional homogeneity is necessary since even small nonuniformities can manifest themselves as significant deviations in device performance. Very large-scale integration (VLSI) is forcing compositional homogeneity and crystalline perfection of ingots to unparalled levels as semiconductor designers drive to smaller and smaller device dimensions and semiconductor manufacturers drive to larger and larger wafer diameters.

Kim et al.[3] show the calculated effects of the intensity of convection on the axial segregation coefficient and the percentage radial segregation for various convection regimes in simulated Bridgman growth. Although good mixing occurs in systems with very intense convection, the time dependency and chaotic nature of the convection often results in compositional fluctuations (i.e., striations) in the final product. In spite of the fact that compositional striations are not produced by steady laminar convection, but significant radial segregation can still be produced. It is expected that the regime where diffusion controlled growth dominates will minimize the radial segregation and allow the accurate prediction of axial segregation in practical crystal growth systems.

To date, diffusion controlled growth has only been achieved in Earth-based melt growth systems of very small diameter or in moderate diameter systems utilizing magnetic field damping of convection. For example, Weinberg[4] was able to achieve diffusion controlled solidification and growth of tin-silver alloys using crucible diameters of 2 mm or less. Samples grown by Weinberg in larger-diameter crucibles exhibited considerable segregation presumably due to buoyancy convection. However, the use of melt stabilizing axial magnetic fields of 30 kG allowed Matthiesen et al.[5] to grow Ga-doped germanium samples of 20-mm diameter under diffusion control.

Many investigators have proposed crystal growth in space to grow materials under diffusion control and preliminary experiments have indeed experienced diffusion control.[6] Motakef[7] used computational fluid dynamics to show the effects of crucible diameter, magnetic field, and g level in obtaining diffusion controlled growth during simulated Bridgman crystal growth of various semiconductor materials (Fig. 1). Based on Motakef's predictions, the g levels anticipated for the space station (10^{-5}–$10^{-6}g$) will only allow diffusion controlled growth of samples up to about 4–8 cm in diameter without the application of magnetic fields. Larger-diameter crystal growth experiments would experience disturbing buoyancy convec-

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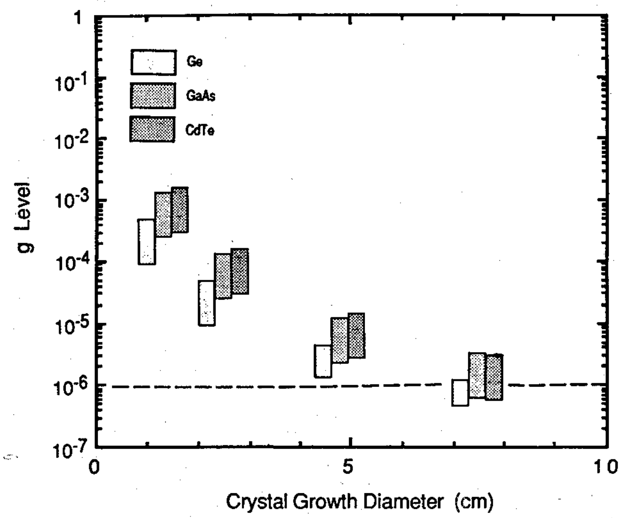

Fig. 1 Range of required gravity levels to achieve diffusion controlled growth for three semiconductors in a directional solidification system (after Motakef[7]).

tion. Additionally, crystal growth of reasonable lengths of materials will require days or weeks for the slow growth processes to occur, and the experiments on the Space Station will likely be subjected to large transient accelerations resulting from crew motion, stationkeeping, valve closures, and other aperiodic disturbances anticipated on that complex facility. In contrast, free-flying research platforms are expected to provide the extremely quiescent conditions necessary for large-diameter crystal growth in space.

Solar Furnace Satellite Concept

Current orbital furnaces are usually based on electric heating, requiring that electricity be either generated by fuel cells, batteries, or solar arrays and then converted into heat. Large-diameter samples will require large amounts of power, and the mass-to-orbit penalties of the traditional approaches listed earlier are expected to be prohibitive.[8,9] A more efficient system would use concentrated solar radiation to directly heat the sample. This can be done by using a concentrating collector to focus solar radiation on the sample. A concentrating solar collector operates by focusing the solar radiation of the concentrator (primary mirror) onto a small target area (the collector). An orbital solar furnace has an advantage over Earth-based units in that the available solar energy has not been diminished by atmospheric effects. Approximately 1350 W/m^2 are constantly available in space, as opposed to a daily peak of less than 1000 W/m^2 on the Earth's surface.

Concentrating solar collectors have already been considered as heat sources for spacecraft power generation. Several forms of lightweight concentrators were studied in the early 1960s, including solid (one piece), collapsible, and inflatable configurations.[8–11] In testing, absorber temperatures ranged from 550 to 1940 K. One notable development was the Sunflower.[10] This was a 9.9-m-diam collapsible collector made up of rigid petals that folded to allow the unit to fit into a 3-m-diam shroud for launching. The Sun's image was focused on a mercury boiler to drive a Brayton-cycle system. In addition, a concentrating collector system has been proposed as an auxiliary power supply for Space Station Freedom. These units are expected to supplement the Station's power supply by 50 kW, and a prototype constructed by Rocketdyne consists of parabolic mirror segments concentrated on a single collector.[11]

It is proposed to develop a solar furnace for in-space materials processing. The proposed system would consist of a solar furnace satellite (SFS) placed into a Sun-synchronous polar orbit of approximately 650 km altitude and serviced by unmanned supply vehicles. The SFS would be placed into orbit by an expendable booster, operate autonomously or via ground control, and would allow sample return to the Earth utilizing the service module. A 650-km Sun-synchronous polar orbit of 98-deg inclination will provide continuous solar exposure allowing uninterrupted processing. In addition, the orbit will automatically precess approximately 1 deg/day to enable the SFS to remain pointed at the sun.[12] Excess process heat will be rejected by thermal radiators, as shown in Fig. 2. The satellite could be stabilized by extendable gravity gradient booms as shown in Fig. 2 or by magnetic torquers and thrusters. The thermal radiators are always in the shadow of the primary mirror and, thus, are expected to be exceptionally efficient. The service modules will be launched by expendable boosters, dock with the SFS, sequentially process samples, detach, and deorbit for recovery after re-entry.

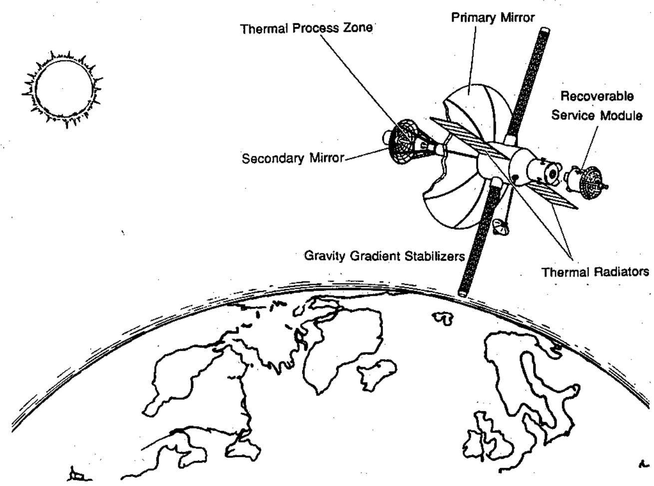

Fig. 2 Preliminary concept of a Solar Furnace Satellite for processing large-diameter crystals in space.

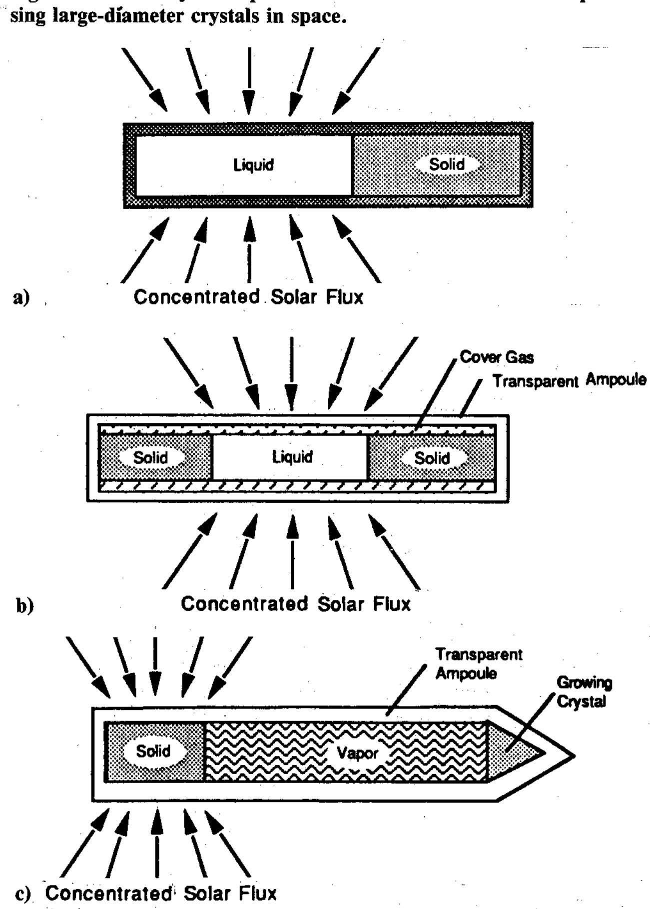

Fig. 3 Axisymmetrical design of the furnace makes the technology potentially suitable for a variety of crystal growth processes: a) Bridgman/Stockbarger; b) floating zone; c) vapor transport.

One of the most beneficial capabilities to be designed into any orbital test facility is the ability to perform a wide variety of experimental tests on a wide variety of materials for a reasonable cost. The SFS technology described here takes advantage of the fact that many common melt-growth processes are performed in a cylindrical crucible (or ampoule), as shown in Fig. 3. The SFS will symmetrically focus the Sun's energy into a fixed focal region through which the samples will either be moved or a gradient freeze technique utilized. Thus, the samples will be melted and then directionally resolidified to yield the desired crystals. The range of processing temperatures and thermal gradients required for the various materials will be achieved by 1) activating or deactivating segments of the primary mirror by rotating them into or out of position, thus increasing or decreasing the power to the sample; 2) shielding portions of the sample in the focal region with a reflector to decrease energy input as described by Conn[13]; 3) applying solar selective coatings to the crucible/ampoule to modulate the solar energy absorbed as well as the infrared energy re-emitted[14]; and/or 4) modulating the amount of heat extracted from the sample with a heat pipe and thermal radiator system.

The primary mirror sizes necessary for processing electronic crystals of current interest were estimated from a straightforward steady-state thermal balance, where

$$\text{power}_{\text{solar radiation}} =$$

$$\text{power}_{\text{conduction}} + \text{power}_{\text{thermal radiation}} + \text{power}_{\text{latent heat}} \qquad (1)$$

It was assumed in these calculations that 1) the mirror's reflectivity is 90%, 2) the solar absorptivity is 0.7 and the thermal emissivity at the melting temperature is 0.3,[15] 3) 100% of the crucible's thermal emittance is emitted to space, and 4) the thermal gradient in the sample is 100°C/cm. The thermal properties of the electronic materials were taken from literature sources.[16-19] The primary mirror size calculated for the solar furnace to grow crystals of various electronic materials up to 20 cm in diameter is shown in Fig. 4. As expected, the higher melting point materials require much larger primary mirrors, up to approximately 12-m diam for a 20-cm-diam silicon crystal.

Projections of the masses for the various subsystems of the SFS are given in Table 1. As shown in Table 1, the projected mass to orbit of the SFS is 1500 kg and will require a Taurus class of booster. Ongoing recurring launches will be confined to the sample laden service module. The service module with about 120 kg of samples is anticipated to weigh 270 kg and will require a Pegasus class of launch vehicle.

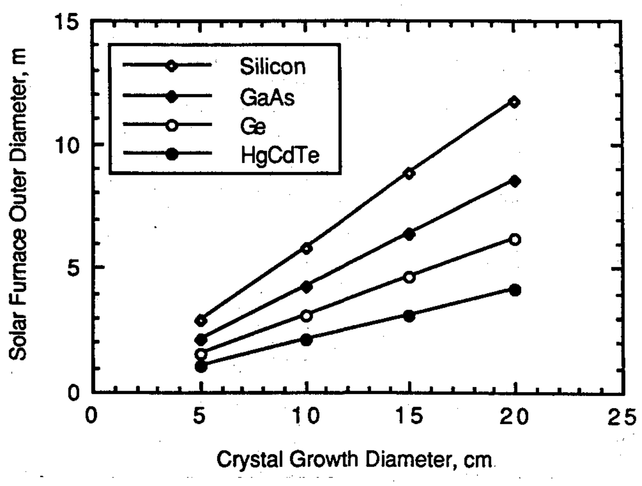

Fig. 4 Estimates of the primary mirror sizes required for processing various electronic materials.

Table 1 Projected mass summary for the Solar Furnace Satellite

Subsystem	Mass, kg
Primary mirror	350
Secondary mirror and controls	75
Structure and mechanics	300
Attitude control	75
Communications/electronics	150
Thermal control	450
Contingency	100
SFS subtotal	1500
Service module w/o samples	150
Samples	120
Service module subtotal	270

Table 2 Residual accelerations expected on the Solar Furnace Satellite

Environment induced	Spacecraft induced
Atmospheric drag	Stationkeeping
Solar radiation	Satellite machinery
Gravity gradient	Attitude control
Oblateness of the Earth	

Anticipated Microgravity Levels

Martin et al.[20] analyzed the various residual accelerations operating on an orbital facility in their design of a very low acceleration research facility. Table 2 lists the accelerations of most importance to the SFS and separates them into environment-induced and spacecraft-induced residual accelerations. Environment-induced accelerations are quasisteady in nature and, thus, are expected to be more deleterious to crystal growth experiments than high-frequency vibrations (> 10 Hz). High-frequency vibrations are usually associated with miscellaneous satellite machinery such as momentum wheels and magnetic torquers for attitude control. Thruster firings to maintain a nominal orbit can be scheduled between crystal growth experiments so as not to degrade the integrity of the experiment.

In low Earth orbits, drag is usually the dominant disturbing acceleration that can degrade the gravity environment of crystal growth experiments. As orbital altitudes increase, the atmosphere gets increasingly thin and the resulting drag forces decrease. Hamacher[21] gives the following equations for atmospheric drag:

$$a_d = C_d(\rho/2)V_s^2(A_{p1}/M) \qquad (2)$$

where

$$V_s = \sqrt{[\mu/(R_e + h)]} \qquad (3)$$

Geyling and Westerman[22] show the variation of atmospheric density with altitude based on the well-known Air Research and Development Command's 1959 Atmosphere. Since a freely falling spacecraft's velocity is uniquely determined based on its altitude as shown by Eq. (3), Eq. (2) was solved for several representative values of A_{p1}/M, and the results are shown in Fig. 5 as a function of altitude. Clearly, an altitude of 650 km puts the deceleration due to atmospheric drag in the 10^{-7}-g range.

Solar radiation pressure arises from momentum transfer due to the photons striking the large projected area of the primary mirror. Hamacher[21] notes that the acceleration due to solar radiation is given by

$$a_{sr} = P_{sr}(A_{p2}/M) \qquad (4)$$

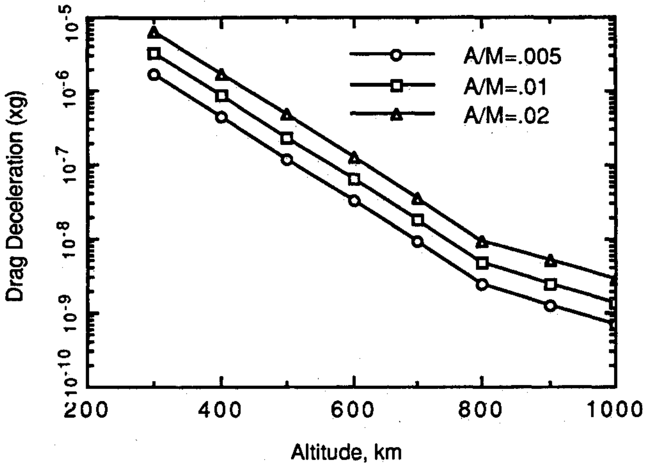

Fig. 5 Nominal *g* levels due to atmospheric drag for the conditions indicated: C_d assumed to be 3.5.

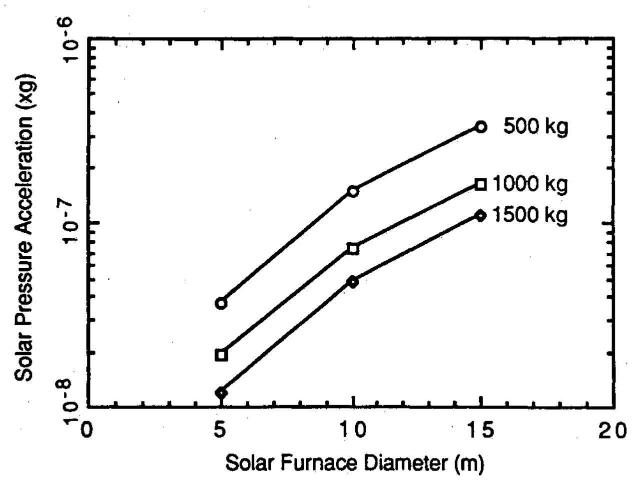

Fig. 6 Nominal *g* levels due to solar radiation pressure for the conditions indicated.

The variation of solar radiation induced acceleration levels with solar mirror diameter calculated for representative values of A_{p2}/M is shown in Fig. 6. The calculated acceleration levels for a 12-m-diam mirror are again in the 10^{-7}-*g* range.

On a free-flying platform, a 0-*g* condition is experienced only by points along the orbital path of the center of mass. This occurs because at all other points the gravitational attraction is not perfectly balanced by the centrifugal acceleration. Olsen and Mockovciak[23] show that the maximum total acceleration for a circular orbit of displacement from the spacecraft center of mass is $0.228\omega^2$ *g*/m, where ω is the orbital rate. For altitudes less than 1000 km, $\omega \sim 1.24 \times 10^{-3}$ s^{-1}, and gravity gradient effects contribute about 4×10^{-7}-*g*/m displacement from the center of mass. Additionally, the absolute acceleration due to the 1-deg/day orbital precession will be approximately 2×10^{-7}-*g*/m displacement from the center of mass. Thus, the molten process zone will have to be located within 1 m from the spacecraft center of mass to maintain gravity gradient and orbital precession induced accelerations in the 10^{-7}-*g* range.

Bauer[24] notes that, although the gravity gradient acceleration levels can be modified by the oblateness of the Earth, the effect is quite small and can be neglected.

Conclusions

Past materials processing in space research and current experimental programs are establishing the benefits of convection-free crystal growth in small-diameter crystal growth systems. However, the development of advanced free-flying platforms with energy efficient furnace technologies is an important national need to enable the next generation of crystal growth experiments targeted toward large-diameter crystal growth. Both the convection experienced in the system and the power required for the experiment increase significantly as the dimensions of the growing crystal increase. This analysis indicates that a free-flying platform utilizing established solar furnace technology could satisfy the demanding power needs as well as the background microgravity levels required for large-diameter crystal growth.

The objective of the Solar Furnace Satellite is to provide a versatile and cost-effective capability for industrially significant crystal growth research in space. It would be capable of processing a wide range of materials utilizing a variety of crystal growth processes. Many of the required technologies and capabilities already exist, although further analyses and experiments are underway to quantify the effects of factors such as pointing misalignment and thermal stability.

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