

A Review of Detached Solidification in Microgravity

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Directional solidification in microgravity has often led to ingots that grew with little or no contact with the ampoule wall. When this occurred, crystallographic perfection was usually greatly improved -- often by several orders of magnitude. We summarize here the experiments that have produced such results.

1. Observations of reduced contact with the ampoule wall.

Many directional solidification experiments have been performed in orbiting spacecraft (microgravity)[1-134]¹. While some of these experiments yielded ingots whose surfaces differed little from those grown on earth, others were vastly different. In vertical directional solidification on earth, the surface of the resulting ingot replicates the surface of the ampoule or crucible from which it was grown, except for the presence of gas bubbles (voids) along the wall. After correcting for thermal contraction, it is the same diameter as its growth container. In contrast, ingots solidified in microgravity frequently have smaller diameters with surface features strikingly different from those of their containers. Some of these features had never been reported from terrestrial experiments.

Below we classify the surface features of materials directionally solidified in microgravity. Note that a given ingot might display several of these features along its length, but never all of them.

1. Isolated voids or bubbles of various sizes, depths and contact angles with the ampoule wall [10-12,15-17,31,32,82,92,93,96,108-110,120].
2. With a triangular or rectangular cross-section ampoule, cylindrical detached surfaces in the corners and a flat surface in contact the wall over most of each face [15,16,30].
3. With a roughened ampoule surface, e.g. with grooves machined in it, contact only on the peaks [39-46,111].
4. Easily slid out of its container, whereas sticking (adhesion) was observed when solidification was carried out on earth under otherwise identical conditions [106,107,126,131].
5. After correcting for thermal contraction, a gap of about 1 to 60 μm between the ingot and the ampoule wall [13,14,33-38,59-66,72,73,47-49,92-95]. Irregular narrow ridges maintained limited contact with the ampoule wall and were predominantly axial. A variety of features were seen in the detached regions, including microfacets and waves or bands normal to the axis [36-38], but never any bubbles. In fact, the presence of surface bubbles evidence for contact of that portion of the ingot with the ampoule wall (i.e., attachment).
6. There was a gap of up to several mm between the ingot and the wall, typically with a wavy surface and often forming an hourglass-shaped neck adjacent to the seed [3,5,8,13,14,19-28,35-39,43,47-58,66,67,69,72-78,86-92,96-105,111,126-129,133,134]. Sometimes there were waves or bands normal to the axis [92,93,95,96]. Although the gap generally extended around the entire periphery, sometimes it was confined to a portion of the surface.

¹ These references are the same as those cited in Table 1. The intent was to include all relevant work to 1998, although that is undoubtedly impossible. Excluded were those studies in which a piston and strong spring were successfully employed to avoid detached solidification.

When early parts were detached (5 or 6 above), the last portion of the ingot to freeze usually replicated the surface of the ampoule, showing that contact eventually became intimate.

Voids (behavior 1) frequently appear on the surface of ingots solidified on earth, but tend to be larger and more frequent on those solidified in microgravity. It is important to recognize that the voids found on the surface of Bridgman-grown crystals do not have the same shape as the gas bubbles on the wall before solidification of the melt. Thus, in a parabolic flight experiment on InSb using a transparent furnace, we saw gas bubbles on the wall move when the freezing interface contacted them [135]. A bubble moved toward and partly onto the interface, so as to minimize the surface energy in the system. If one looks carefully at such a cavity on a grown crystal, it can be seen that the contact angle to the ampoule varies as one moves around the periphery of the cavity. This variation is a manifestation of the interaction between the growing crystal and the bubble.

Behaviors 2 and 3 are not surprising, as one would not expect non-wetting (i.e., high contact angle) liquids to penetrate cavities. (In the surface science literature, this is often called “composite wetting.”) Such partial detachment also has been obtained on earth using a triangular ampoule [136] or an ampoule with a rough surface [e.g.,44,137], lining, or coating [e.g.,138,139].

Here, we are concerned primarily with behaviors 5 and 6 above. These differ from all prior terrestrial experience and were completely unexpected prior to Skylab. We prefer the term “detached solidification” for such behavior [140-144], while others favor “dewetting” [e.g.,43,109].

Although detached solidification has been observed predominantly with semiconductors, it has also commonly been observed with metals [1,3,5,8,13-16,27,28,132,133] and to a lesser extent with inorganic compounds [112-117]. This predominance mostly reflects the fact that most flight experiments on directional solidification have been performed on semiconductors.

Detached solidification has been observed at both fast and slow freezing rates. Sometimes it occurred with one dopant and not with others. The type of detachment, indeed even whether detachment occurred or not, has not been reproducible.

Some investigators have chosen to avoid detached solidification by using a spring or packing to press a plug (piston) against the end of the melt [e.g., 144-148], although such arrangements have not always prevented detachment [23,47-55,59-66,116,117,124,125]. A strong spring appears to be necessary.

It has been claimed that detachment is sensitive to the residual acceleration in the spacecraft. Unfortunately, there have been so few measurements of residual acceleration, particularly the average value, that one cannot judge the validity of this claim from experimental evidence.

2. Influence of detachment on crystallographic perfection and compositional homogeneity

As with surface appearance, a wide variety of properties has been observed in ingots exhibiting detachment. It is interesting to note that there was seldom any relationship between internal defects or composition variations and the longitudinal ridges or circumferential bands on the surface.

Axial variations in composition with detached solidification ranged from that expected for diffusion-control [36-44,50-57,66,67] to those corresponding to convective mixing [39,41,45,46,69,72-77,127]. Sometimes a radial variation in composition was measured [50,55,65,66,83-85], especially near the detached surface [57,58]. Impurity striations were

occasionally seen, especially near the surface [47-49,59-64,66,89-93]. Some detached surfaces were inadvertently coated with oxide [39,80], whereas even adsorbed oxygen could not be detected in Refs [33,34]. An interesting result was obtained in Skylab experiments on GaSb-InSb alloys [53,55]. Large changes (jumps) in composition occurred across twin boundaries only in the detached portions of ingots.

In detached solidification, the melt immediately adjacent to the freezing interface is not in contact with the ampoule wall [43,109,140-144]. A meniscus connects the outer edge of the growing crystal with the ampoule wall. With temperature and concentration gradients along the surface of a free melt, one expects Marangoni convection [e.g., 53,55,141,149]. Such convection must manifest itself as perturbations to the axial and radial variations in composition of the ingot. As noted above, flight experiments with detachment yielded a wide spectrum of results. In some cases, axial concentration profiles corresponded to diffusion-controlled conditions. In other cases, there seemed to be clear evidence for Marangoni convection, ranging from gentle to vigorous². Indeed, the rapid particle motion observed in the videotape of PbBr₂ solidification in microgravity is readily attributable to Marangoni convection about flattened bubbles on the wall [114-117]. Similarly, Marangoni convection was held responsible for the particle motion observed about bubbles formed at the freezing interface of CsCl growing in microgravity [25].

The central question is, why was Marangoni convection not always manifested with detached solidification? There are several possible explanations. If the meniscus between the growing crystal and ampoule wall is very narrow, the region of perturbed composition due to convection should also be very localized near the wall [141]. Thus, even with Marangoni convection, one might still achieve the diffusion-controlled axial concentration profile, particularly if the freezing rate is high. In many flight experiments, only axial variations in composition were determined, with no measurements of the radial variations that would have more definitively revealed the presence or absence of convection.

Another possible explanation for diffusion-controlled segregation with detached solidification invokes a surface-active impurity that concentrates on the meniscus surface. One would expect, for example, that dissolved oxygen would concentrate on the surface of semiconductor and metal melts. Such surfactant impurities are known to strongly inhibit the movement of a free liquid surface. For example, a surfactant can stop the Marangoni motion of a gas bubble in a temperature gradient and retard its rise velocity in a gravitational field [e.g.,150]. The influence of a surfactant increases as the bubble size decreases. Thus, if oxygen is present in a semiconductor melt and concentrates at free surfaces, we would not expect Marangoni convection to occur for very narrow gaps or very small bubbles.

A third possibility is the formation of an oxide film as a second phase on the surface of the melt. An oxide skin was sometimes deliberately applied [1,3,6,29], and other times inadvertently formed [39,79], on the feed rods for microgravity experiments. Sometimes the resulting ingot was partially detached from the skin. When the skin adhered, the surface showed crinkles and cracks due to the volume change on solidification.

Crystallographic perfection was usually much greater when detached solidification occurred, while there was negligible difference from earth-processed materials when the solid was fully attached. Twin and grain boundary nucleation was greatly reduced, and sometimes occurred only where the ingot contacted the ampoule wall [13,14,19-24,33-55,59-64,66,78,87,88,96]. Dislocation etch pit densities were less, often orders of magnitude so, when the solidification had been detached [19-24,33,34,36-40,66,67,70,71,78,86,89-91,97-103,116,117,124,125]. In

² The surface bands and internal striations noted above may have been caused by fluctuating or oscillatory Marangoni convection. Alternately, they might be attributed to vibrations transmitted through the spacecraft, so-called "g-jitter."

semiconductors, this higher perfection led to substantial increases in charge carrier mobility [33,34,126,131].

The decrease in dislocation density is easily understood if we consider the stresses arising in directional solidification in a container. Calculations have been performed of the stress in the growing ingot, assuming no plastic deformation [137,151-153]. When the solid adheres to its container, the difference between their thermal expansion coefficients leads to stress levels two orders of magnitude larger than those caused by temperature gradients within the solid. Via dislocation multiplication, this calculated stress is transformed to an increased density of dislocations. Thus detachment should result in an approximate two orders of magnitude decline in dislocation density. It is relevant to note that with normal attached solidification on earth, the dislocation density of CdTe [154] and GaSb [137] decreased as the contact angle between their melts and the ampoule wall increased (i.e., wetting decreased). (One would expect that the adhesion of a crystal to its ampoule increases as wetting by its melt increases, although this is not necessary true and has not been experimentally verified.)

The reason for the beneficial effect of detachment in reducing grain and twin nucleation is less clear. It is generally believed that grains and twins nucleate preferentially at the ampoule wall. So it is not surprising that detachment reduces nucleation. But why is nucleation so highly favored at the wall? One thought is that the high stress caused by adhesion cause mechanical nucleation of grains and twins within the solid just as it causes multiplication of dislocations. However, experiments on $\text{In}_x\text{Ga}_{1-x}\text{Sb}$ [155] and on $\text{Cd}_x\text{Zn}_{1-x}\text{Te}$ [156] showed that mechanical stress never causes formation of twins or grains in these materials, but only dislocation slip. We are convinced that this conclusion is valid for the entire class of diamond and zincblende crystal structure materials. We believe it is mechanical stress at the growth interface that is responsible for nucleation of most, if not all, grains and twins, during solidification, as demonstrated recently in naphthalene [157]. And where is mechanical stress the largest on the freezing interface? Adjacent to the surface of the ampoule when the solid adheres to it.

3. Summary of microgravity experiments

Table 1 summarizes microgravity experiments showing detached solidification, along with some experiments that did not show detachment. We attempted to be comprehensive for those showing detachment, and apologize for any works that have been inadvertently omitted. It was frequently difficult to summarize results, and, again, we apologize for errors that appear here. Where possible, a draft of our summary was sent to one or more of the authors. In response, we often received a correction or additional information. We would very much appreciate additional corrections and information from readers of the present paper.

Not included in Table 1 are microgravity experiments that successfully employed pistons and strong springs to avoid detached solidification.

Some words of explanation are necessary for the information contained in Table 1. The first column refers to the feed material, and not to the product composition. Impurity doping levels are sometimes given in the usual semiconductor fashion as atoms per cm^3 , and other times as atom percent (%a), weight percent (%w), or volume percent (%v).

The second column in Table 1 refers to the container used for the experiment. These were all cylindrical, unless otherwise noted. When “quartz” is shown, the container was fused silica (SiO_2) sealed at both ends, unless a cylinder with plugs at the ends is indicated. For other container materials that cannot be fused (such as graphite, SiC and BN), the container was either a crucible sealed at only one end, or a cylindrical tube with plugs in both ends. In some experiments, a “skin” was formed directly on the feed ingot.

The gas pressure shown in column 2 was that when the ampoule or surrounding cartridge was sealed, unless otherwise indicated. It should be noted that recent work [158] showed that quartz ampoules can contribute gases, mostly hydrogen, up to a pressure of about 10 torr. Coatings and linings also can outgas. Repeated baking and evacuation reduce outgassing, but do not eliminate it. Diffusion through the quartz walls occurs at high temperatures.

The third column in Table 1 gives the diameter D and length L of the feed material. These dimensions were almost always smaller than those of the ampoule, and sometimes considerably so.

The fourth column in Table 1 gives the solidification method. Here, GF denotes the gradient freeze technique, i.e. a temperature gradient was imposed on the material and then the power was gradually reduced in order to cause directional solidification. "Translated" indicates that the ampoule was translated through the furnace, or *vice versa*. In the literature, the freezing rate was usually assumed to be equal to the translation rate, or, for GF, equal to the temperature lowering rate divided by the temperature gradient G . (Note that many experimental and theoretical studies have shown that the freezing rate can deviate considerably from the translation rate, especially near the ends of the sample. Similarly, in the GF technique the true freezing rate must be greater than that calculated from the furnace G because G in the experimental material must be less than that in the furnace.)

The fifth column in Table 1 gives the soak time at constant temperature before solidification, the temperature gradient G , and the cooling conditions. Usually, G was the temperature gradient in the furnace, not in the sample.

The sixth column in Table 1 gives the mission and/or spacecraft, the hardware used for the experiment, and the year the experiment was performed.

The seventh column describes the appearance of the surface of the ingot. "Detached" indicates that some gap existed between the ingot and the ampoule, beyond that caused by thermal contraction. "Attached" and "wetted" signify that the author believed the ingot was in intimate contact with the ampoule wall during solidification. "SEM" denotes scanning electron microscopy. The presence of bubbles (voids) on the surface indicates attachment of the adjacent material.

The eighth column compares the interior of the ingots grown in microgravity to those grown on earth under otherwise identical conditions. "EPD" denotes etch pit density, and is understood to be the density of dislocations. "Segregation" refers to the variation in composition or impurity doping. "Diffusion-controlled segregation" indicates that the axial variation in doping was that expected for convective velocities much less than the freezing rate. "Striations" indicates bands revealed by etching. A striation is usually considered to result from a sharp variation in doping arising from a rapid change in freezing rate and/or convection in the melt, thereby demarking the position of the freezing interface at that time.

4. Discussion and Conclusions

We see that detached solidification in microgravity can take several forms and has occurred for many materials over a wide range of conditions. It is a phenomenon worth investigating not only because of its novel character, but also because of the tremendous improvement in crystallographic perfection that typically accompanies it.

We attempted to correlate the empirical information presented in Table 1. Data were excluded for the following reasons:

- Square or triangular cross-section ampoules, which always gave detachment at the corners but not on the faces [1,30].

- Artificially roughened ampoules, which always gave detachment at least on the valleys [27,36-46,].
- Metallic ampoules, which did not give detachment [2,3].

Linear regression analysis yielded the following equation:

$$D = 0.89 - 0.50 S - 0.66 M - 1.0 OS + 0.27 C - 0.18 P + 0.65 LV + 0.35 MV + 0.20 HV \quad (1)$$

Here:

- D represents detachment, with a value of 1 if a substantial portion of the solid grew detached to produce a surface noticeably different from that of its container, 0.5 if it slid out of the container more easily than from earth but retained the shiny surface of the ampoule wall, and 0 if the solid grew attached.
- S represents a semiconductor material, with a value of 1 for a semiconductor and 0 for others.
- M represents of metal or metal alloy, with a value of 1 for a metal and 0 for others.
- OS represents an organic compound or inorganic salt, with a value of 1 for either of these.
- C represents the crucible, with a value of 1 for graphite, silicon carbide, boron nitride or carbon-coated quartz. A value of 0 was assigned for uncoated oxide containers.
- P represents the pressure under which the ampoule was sealed, with a value of 1 for a pressure above 10 torr, and 0 for a lower pressure.
- LV was assigned a value of 1 for a low freezing velocity, $\ll 1$ cm / h.
- MV was assigned a value of 1 for a medium freezing velocity, ~ 1 cm / h.
- HV was assigned a value of 1 for a high freezing velocity, $\gg 1$ cm / h.

Those parameters with more positive (or less negative) coefficients favored detachment. Thus equation 1 indicates that detachment was favored for semiconductors in non-sticking ampoules sealed in a vacuum using a low freezing rate. However, equation 1 correlates the data in Table 1 poorly, with only 32% of the variation in detachment explained by the correlation (i.e., $r^2 = 0.32$). Figure 1 shows predicted versus observed detachment. The confidence limits on the constants are particularly broad for the materials solidified, i.e. one really cannot say that semiconductors are more likely to show detachment than other materials. The conclusions about use of non-sticking ampoules and low freezing rates are more firm. Thus other factors, not reported, appear to have played major roles in determining detachment. These factors probably include modification of surface properties by impurities or oxide, and accelerations within the spacecraft. In order to fully understand detached solidification, both theoretical modeling and careful experiments will be required.

We believe the only model consistent with experimental observations and theoretical considerations is one in which a meniscus connects the periphery of the growing crystal with the ampoule wall, i.e. the Moving Meniscus Model [140-144, 159]. (The melt cannot be levitated in cylindrical form in the ampoule, as some had visualized.) An important characteristic of this model is that the meniscus must move along the ampoule surface. We believe this model has the potential to explain all observed phenomena, as well as to make possible the reproducible achievement of detached solidification in microgravity, and possibly on earth as well.

Table 1. Directional solidification experiments performed in space without having avoided detachment by a piston and strong spring.

Material & Growth dir'n	Ampoule & fill gas	Feed, melt, growth	Method & freeze rate	Thermal conditions	Carrier, furnace, year of flight(s)	Results: surface	Interior compared to earth-grown ingots	Authors & references
Ag	TiO ₂ skin, square cross section	D ~ 8 mm L = 49 mm	6 mm/hr	G = 200-300 K/cm	TEXUS-9 rocket	Detached along corners.		Sprenger [1]
Ag (+ 2.8 %v W particles)	Ni		GF	G = 8 - 16 K/cm. Rapid cooling.	TEXUS-20 rocket. TEM 01 Isothermal Furnace	“The crucible wall ... completely wetted ...”	No macro sedimentation of particles as on earth.	Froyen <i>et al.</i> [2]
Ag-Cu (eutectic: 28.1% w Cu)	Graphite. Some with Al ₂ O ₃ or Ni skin. 750 torr Ar	D = 5 mm L = 1 - 8 mm with graphite spacers betw.	~360mm/hr	Cool ~ 2300 K/hr (molten for ~ 7 min)	Spacelab-1 (Shuttle). Isothermal Heating Facility. 1983	Those with Al ₂ O ₃ skin had large areas detached, with facets. Others attached.	Lamellae ~2X larger. Many more rods and broken lamellae, fewer dendrites.	Barbieri <i>et al.</i> [3]
Ag₄RbI₅	Quartz		1 GF, 1 translated at 5 mm/hr	G = 10 K/cm. 1 cooled at 12.5 K/hr, 1 translated	MIR. Crystallizator CSK-1 1989	SEM shows same morphology as from earth.	No cracks. Fewer photoluminesc peaks. Sharper X-ray diffract.	Regel <i>et al.</i> [4]
Al	Quartz. ~ 0.1 torr Ar	D = 6.5 mm L = 55 mm	Translated 11 - 22.6 mm/hr	Soak 10 - 120 min.	Salyut-6. Kristall facility. 1980	“Shrinkage” larger in part with smaller diameter.		Fuchs <i>et al.</i> [5]
Al (+ 4% Cu)	Quartz. ~ 0.1 torr Ar	D = 11.5 mm L = 100 mm	GF 11 - 22.6 mm/hr	Soak 138-420 min. G = 30-40 K/cm. Cool 11.3-45 K/hr	Salyut-6. Splav facility. 1980	Irregular and wavy.		Fuchs <i>et al.</i> [5]
Al (+ 0.2-0.5wt% SiC & Al ₂ O ₃ particles)	Graphite. Al ₂ O ₃ skin. Vacuum.	D = 10 mm L = 80 mm		Soak 40 min at 800°C. Cool 3600 K/hr	Spacelab-1 (Shuttle). 1983	Attached to oxide skin. Crinkled and wavy.	Distribution of SiC more uniform. Microhardness 20% higher. Better adhesion of particles.	Froyen & Deruyttere [6]
Al (several alloys)	Graphite. Some with Al ₂ O ₃ skin. 750 torr.	D = 5 mm L ~ 8 mm	GF ~360 mm/hr	Cool ~ 1800 K/hr	Spacelab-1 (Shuttle). Isothermal Heating Facility. 1983	Strong adhesion to oxide skin.		Barbieri <i>et al.</i> [3]
Al (+ 1-5% a Zn)	SiC. Vacuum				Spacelab-1 (Shuttle) Gradient Heat. Fac. 1983	“No evidence of wetting” Sample moved to hot part.		Potard and Morgand [7]
Al - Cu (eutectic: 33.0% w Cu)	Graphite	D = 6.25 mm L = 12.7 mm	GF	Soak 1 hr. G = 45 K/cm. Cool 144 K/hr	Skylab 3 & 4. Westinghouse GF. 1974	Reduced diameters with hourglass shapes, slight from Skylab 4.		Hasemeyer <i>et al.</i> [8,9]
Al-Cu (eutectic: 33.0% w Cu)	Ar	D = 5 mm L = 150 mm		No soak	Spacelab 1 (Shuttle). 1983	Attached. Spherical bubbles (0.5 to 2 mm) on the last third.	No change in lamellar spacing or regularity.	Favier <i>et al.</i> [10-12]

Al - Ni (eutectic: 6.1%w Ni)	Graphite. 2×10^{-3} torr	D = 7 mm L = 70 mm	GF 20 and 200 mm/hr	Cool 18 or 90 K/hr	MIR. Crystallizator CSK-1 1987	Detached	NiAl ₃ rods axial from start. Spacing 9% larger at 20 mm/hr, 13% at 200mm/h	Regel <i>et al.</i> [13,14]
Bi (+ 0.5%a Sb)	Carbon-coated quartz	D = 9 mm L = 55 mm	Translated 11.3 mm/hr for 65 mm	G ~ 20 K/cm	Salyut-6. Kristall facility. 1978	Many bubbles. Otherwise attached.	Inhomogeneous for 25mm, attributed to rapid growth, then diffusion controlled segregation.	Schneider <i>et al.</i> [15,16]
Bi (+ 1%a Sb)	Carbon-coated quartz rectangular mould.	1.6 x 1.6 x 28 mm. 1.2 x 5 x 55 mm.	GF	G = 5 K/cm and G = 11 K/cm. Cooled 3 K/hr for 24 hr.	Salyut 6. Splav 01. 1978	Rounded detached corners. Flat attached faces with bubbles.	Inhomogeneous for 7mm, attributed to rapid growth, then diffusion controlled segregation.	Schneider <i>et al.</i> [15,16]
(Bi_{1-x}Sb_x)₂Te₃	Quartz		10.8 mm/hr	G = 70 K/cm	Salyut-6. Halong-2&3. 1980	Pores, holes with smooth surfaces, pores with steps.		Zusman <i>et al.</i> [17]
CBr₄ (impure)	Pyrex. 760 torr Ar, H ₂ or N ₂	D = 10 mm L = 100 mm θ low	~ 36 mm/hr	G = 5 K/cm. Passive cooling upon launch.	SPAR Black Brandt rocket (~ 5 min). 1976	Attached with no bubbles.	Bubbles formed, moved little, incorporated in dendritic solid.	Papazian and Wilcox [18]
CdTe (+ 4% Zn)	Quartz	D = 15 mm	Translated 1.6 mm/hr	Heat 2 K/min. Soak 2 hr. Cool 120 K/hr. G = 33 K/cm	USML-1 (Shuttle). Crystal Growth Furnace. 1992	~ 5 mm detachment on one side at end of cone, cellular partial contact, then full contact.	No grain or twin nucleation while detached. Much lower stress and EPD.	Larson <i>et al.</i> [19,20]
CdTe (+ 4% Zn)	Quartz	D = 15 mm seed D 6 mm	Translated 1.6 mm/hr	G = 35 K/cm	USML-2 (Shuttle). Crystal Growth Furnace. 1995	Fully detached neck for 22 mm, partial contact 28 mm.	No twinning in detached. Diffusion controlled segregation. EPD 800 (8×10^5 from earth).	Larson <i>et al.</i> [21-24]
CsCl (+ 1%w ~40μm Pb & gas bub)			GF ~14 mm/hr (measured)		Shuttle. MAUS. 1983	Attached (adhered)	Global circulation of Pb particles. Bubble nucleation & growth.	Klein <i>et al.</i> [25,26]
Fe (Cast iron: 3.9%w C, 1.5%w Si)	Al ₂ O ₃ skin	D = 6.5 mm L = 150 mm	Translated 6, 24, 42 mm/hr	G = 200-300 K/cm	Spacelab-1 (Shuttle). Isothermal Heating Facility. 1983	Gap between ingot and skin. Ingot separated into two parts.		Sprenger, Luyendijk [1,27,28]
Fe (Cast iron: 3 - 4% C)	Al ₂ O ₃ skin, ~ 80μm thick.	D = 7 mm L = 150 mm	6-18mm/hr	Heat to 1350°C. Soak 5 min. G = 200-300 K/cm	D-1 (Shuttle). Isothermal Heating Facility. 1985	Attached to Al ₂ O ₃ skin.	No pores or cavities.	Sprenger [29]
GaAs	BN triangular prism				MIR. Crater.	Detached from corners. Contact with faces.		Markov [30]
GaP <111>	Quartz	D = 9 mm	Zone melt with 3-5mm zone	Soak 1000-1060°C for 15 hr. G = 20 - 40 K/cm	Salyut-6. Kristall facility	Attached. Some bubbles.	EPD 10^4 - 10^5 cm ² . Electrophysical properties similar.	Regel <i>et al.</i> [31,32]

GaSb Polycrystalline	Carbon-coated quartz. Conical front end. Graphite spacer tail end. ~10 ⁻⁶ torr	D = 8 mm L = 39 mm	Translated 11.3 mm/hr	Soak 90 min. Translate 5.5 hr	Salyut-6. Kristall facility. ~ 1980	Detached except for ring near hemispheric front end. Ridges just after ring, some normal to growth, some zig-zag, some attached. Detached parts rough with some microfacets.	EPD 10X less. Grain boundaries 15X fewer. Mobility 40% higher. No oxide by electron channeling. Oxygen <10 ¹⁶ /cm ² by Rutherford back scattering.	Lendvay, Regel <i>et al.</i> [33,34]
GaSb (+ 1%a Te) <111>Ga	Quartz. 5x10 ⁻³ torr	D = 7 mm	GF ~ 10 mm/hr	G = 25 K/cm	Mir-Soyuz TM-3. Crystallizator CSK1. 1987	Asymmetric neck after seed, 7 mm long with max gap 1.1 mm & ridges mainly axial, intricate structure. Rough.	More uniform resistivity, higher perfection, no striations. Lamellar twins at shoulder. On earth, twins grew from wall.	Regel <i>et al.</i> [13,14,35]
GaSb (undoped) <111>B(Sb)	Sand blasted quartz, carbon cloth at ends. 10 ⁻⁶ torr	D = 6 mm L = 30 mm Ampoule 10 mm ID	GF 10-20mm/hr	Feed rod entirely melted. 8 hr growth	China Returnable Satellite - 14. 1992	Photo shows detached at least 1/2 of length, with sharp variations in gap width.	Polycrystalline. Ground-based control adhered to ampoule wall.	Ge, Nishinaga <i>et al.</i> [36-38]
GaSb (Te-doped) <111>B(Sb)	Quartz, carbon cloth at ends. 10 ⁻⁶ torr	D = 6 mm L = 30 mm Ampoule 10 mm ID	GF 10-20mm/hr	All but 4 mm of feed rod melted. 8 hr growth.	China Returnable Satellite - 14. 1992	Dia < seed for 12.5 cm. ~3 mm gap and wavy. Then attached. Photo shows irregular axial ridges and faint lines normal to axis. Shiny & metallic.	Single. No striations. Diffusion-controlled axial seg'n. Twinning begins near attachment. EPD decreases to 0 in detached, increases steeply after attached.	Ge, Nishinaga <i>et al.</i> [36-38]
GaSb (undoped & + 1%a InSb)	Quartz tube with machined spiral groove.	D = 10 mm L = 70 mm	Translated 0.36 mm/hr	Seeds accidentally entirely melted. G = 40 K/cm	EURECA. Automatic Mirror Furnace. 1992	Detached in beginning, then slight contact at sharp ridges at top of screw thread machined in crucible. Attached at end.	Began poly, ended single. Quality increased where detached, degraded where attached. Diffusion controlled axial seg'n.	Duffar <i>et al.</i> [27,39-44]
GaSb (5x10 ¹⁸ Te/cm ³ or 9%a In)	Quartz tube with 1mm grooves. Gas getter. ~10 ⁻² torr after expt.	D = 14 mm. Te-doped L= 120 mm. In-doped L = 70 mm.	GF Te: 4.0-4.5 mm/hr. In: 2.2-3.4 mm/hr.	Te: G = 18-28 K/cm. In: G = 25-40 K/cm	D2 (Shuttle). Gradient Heating Facility. 1993	Detached except at 0.15 mm flats on top of screw thread and where In-doped material was dendritic.	Grain and twin nucleation where attached and at silica dust on surface. Segregation indicates strong mixing.	Duffar <i>et al.</i> [27,39,41, 45,46]
GaSb (Te-doped, high resistivity) <111>B	Quartz. Quartz piston & spring. 400 torr Ar	Feed: D = 4.42 mm L = 35 mm Ampoule: D = 4.49 mm	GF ~ 4 mm/hr	Soaked 3 hr at 795 C. G ~ 52 K/cm Cooled 18 K/hr	MIR. QUELD. 1996	Two of three detached from beginning for 1.5 & 2 mm, then ~ axial ridges in contact.	Less axial segregation. No influence on EPD. Single crystal from space, polycrystalline from earth.	Redden & Mickleth. [47-49]

Ga_{1-x}In_xSb (x = 0.1, 0.3, 0.5)	Carbon-coated quartz. Three graphite spacers sep'd by quartz wool at each end. 10 torr He.	D = 8 mm L = 90 mm	GF ~ 8 mm/hr, increasing down ingot.	Soak 16 hr at 960°C. Melt back ~ 1/2. Initial G ~ 80 K/cm. Cool 36 K/hr for 8.3 hr.	Skylab 3. Westinghouse GF. 1974	Wavy surface with smaller diameter. Much smaller diameter in 2 areas for x = 0.1.	Mostly twin boundaries. 54% fewer boundaries. Twins seldom nucleate in space. Where detached, large radial variation in comp'n. with ~2x changes across twins.	Wilcox <i>et al.</i> [27,50-55]
Ga_{1-x}In_xSb (x = 0.1, 0.3, 0.5)	Same as above	D = 8 mm L = 90 mm	GF, ~ 8mm/hr, increasing down ingot	Soaked 16 hr at 1020°C to melt back ~1/2. Initial G = 80 K/cm. Cooled 36 K/hr	Skylab 4. Westinghouse GF. 1974	Shiny, no gap apparent.	Mostly twin boundaries. 37% fewer boundaries. Diffusion controlled segregation.	Wilcox <i>et al.</i> [27,50-55]
Ga_{0.8}In_{0.2}Sb	Part BN, part quartz.					Quartz: attached. BN: ~ 40 μm gap for 5 cm		Duffar [43,56]
Ge (8x10 ¹⁶ Ga, 4x10 ¹⁴ Sb, or 2x10 ¹⁵ B/cm ³) <111>	Graphite. 10 ⁴ torr		GF 18 mm/hr	Soak ~ 2 hr at 1000C. Cool 36 K/hr.	Skylab 3. Westinghouse GF. 1974	Smooth, necked in. Most pronounced detachment for Ga-doped, ~ 1 cm long.	Resistivity fluctuations ~5X less from space. Less axial and radial segregation.	Yue and Voltmer [9,27,57, 58]
Ge (+ 10 ¹⁹ Ga/cm ³) <111>	Quartz. Graphite end caps for CID. Quartz wool packing. 40 torr Ar.	D = 8.43 mm L = 95mm	GF Increased from 0 to ~36mm/hr. CID reveal no fluct'ns.	Heat 3.5 hr. Soak 2 hr. G = 50 K/cm. Cool 144 K/hr.	Apollo-Soyuz Test Project. Westinghouse GF. 1975	Random network of ridges 1-5 μm high, reducing contact to < 1% of surface.	Axial & radial variations in doping. Fluctuations on and near small (111) facet along one side. Many fewer grains & twins.	Witt <i>et al.</i> [9,27,59-64]
Ge (+ 0.7-1% a Si, 1-2x10 ¹⁷ Sb/cm ³) <111>	Carbon-coated quartz. 10 ⁴ torr	L = 38 mm	GF	G = 30-40 K/cm	Apollo-Soyuz Test Project. Westinghouse GF. 1975	Detached.	No irregularities, cracks or bubbles. Large radial variation in Si, opposite variation in Sb conc.	Zemskov [65,66]
Ge (+ P or Zn)	Graphite-lined quartz or graphite. 10 ⁵ torr	D = 8 mm	GF ~420 mm/hr	100 s to heat. 80 s to melt. 400 s to freeze.	Mir rocket (10 min). BKT exothermic furnace. 1976 - 1980	Contacted walls only in separate small areas.	Gas inclusions. Single crystals compared to polycrystals from earth. EPD 10 ² -10 ³ lower. Uniform doping.	Vlasenko <i>et al.</i> [66,67]
Ge (+ 2x10 ¹⁷ Ga, 1.5x10 ¹⁸ Sb/cm ³)	Carbon-coated quartz.	D = 12 mm L=38-52 mm	Translated 11.3 - 22.5 mm/hr	Soak 2 hr. G = 70-80 K/cm	Salyut-6. Kristall facility. ~ 1978 - 1982	Gap 40 - 60 μm wide & wavy. Scattered peaks and ridges in contact with wall.	EPD 10 ² - 10 ³ /cm ² . Striations.	through Avduevsky [66]
Ge (10 ¹⁸ Ga/cm ³)	Carbon-coated quartz	D = 9 mm L= 39-47 mm	Translated 11.3 mm/hr		Salyut-6. Kristall. ~ 1978 - 1982	Detached over ~ 1/4.	Variation of resistivity 3-4 times lower.	Khryapov <i>et al.</i> [66,68,69]

Ge (+ 10 ¹⁷ Ga/cm ³)	Carbon-coated quartz	D = 9.1 mm L = 60 mm	Translated 11.3 mm/hr		Salyut-6. Kristall.	Irregular lateral mounds and longitudinal ridges in contact.	EPD 2x10 ³ /cm ² (earth 2x10 ⁵ cm ⁻²). Axial segregation reduced.	Markov <i>et al.</i> [70,71]
Ge (+ 10 ²⁰ In/cm ³) <111>	Carbon-coated quartz. Graphite end supports. 10 ⁻⁵ torr	D = 7.8 mm L = 72 mm	Translated 11.3 mm/hr	Soak 1 hr at 1100°C to melt back 14 mm.	Salyut-6. Kristall. 1980	~ 25 mm partial or fully detached with ~ 0.3 mm gap.	Gas bubble on axis near seed. EPD ~ 10 ³ /cm ² . Lower resistivity & higher perfection. Less axial segregation.	Calzadilla <i>et al.</i> [66,72-77]
Ge (p-type, Zn+Sb; p-type, P+Zn) <111>	Quartz. 10 ⁻⁴ torr	L = 40 mm	GF ~360 mm/hr	100 s to heat. Melted ~20 mm	Exothermic furnace. ~1983	Wavy with over 99% detached.	EPD reduced to 10 ² /cm ² from 10 ⁵ - 10 ⁶ /cm ² in seed. Single from space, polycrystal from earth.	Chernov <i>et al.</i> [78]
Ge (+5x10 ¹⁸ Ga/cm ³) <100>	Part in quartz or Pyrex, part free. 760 torr Ar	D = 6 mm	GF	G = 125 K/cm with quartz. G = 95 K/cm with Pyrex. Melted back ~20 mm	MASER 2 rocket (7 min). Mirror furnace. 1990	Regular ridges in growth direction with quartz. Attached to Pyrex. Cracks in free part, attributed to Ge oxide.	Reduced axial segregation in material grown detached.	Tilberg & Carlberg [79]
Ge	Quartz. Carbon sheets at ends.	D = 7 mm L = 100 mm	360 mm/hr by CCD camera. Grew 7 mm		TR-IA rocket (6 min). Transparent furnace. 1992	Strong adhesion to ampoule and carbon sheets at ends. Crack in ampoule at end of growth.	Convex interface. EPD ~ 10 ⁶ /cm ² (slightly lower)	Nishinaga <i>et al.</i> [80,81]
Ge (Ga doped)	Part in quartz, 7 mm free. ~ 10 ⁻⁶ torr Ar	D = 6 mm	GF 360 - 468 mm/hr	G = 35 K/cm	MASER-2 rocket. Swedish mirror Crystal Growth Furnace.	Large bubbles on part in quartz.	Radial variation in Ga attributed to Marangoni convection in uncovered part.	Camel & Tison [82]
Hg_{0.78}Cd_{0.22}Te	Quartz		GF 2-12 mm/hr (Syrena 1) 12-50 mm/hr (Syrena 2)	Soak 2 hr at 500 - 900°C, expt. 37 hr (Syrena 1). Soak 4 hr 45 min, expt 6 hr (Syrena 2). G = 30-40 K/cm.	Salyut-6. Splav-01. 1978	Detached.	Homogeneous with no cavities when < 3mm/hr. Increasing inhomogen. & density of cavities when > 3 mm/hr. Skin enriched in Cd.	Galazka, <i>et al.</i> [66,83-85]
HgCdTe (~ 20% Cd)		D = 8 mm L=15-30mm	GF	Cool 11 K/hr (#1) and 2.8 K/hr (#2)	Salyut-6. Splav-01	Limited contacts with ampoule wall.	EPD 10 ⁴ /cm ² (earth 10 ⁶ /cm ²). Skin enriched in Cd.	Kurbatov <i>et al.</i> [66,86]
Hg_{0.84}Zn_{0.16}Te	Quartz. Quartz wool at end.		Translated 0.15mm/hr	Soak 10 hr. Translate 39 hr to grow 5.7 mm.	USML-1 (Shuttle). Crystal Growth Furnace. 1992	Mostly detached. Smooth with crinkles and some hills. Part matte finish.	Much more asymmetric concave interface. Low strain and no twinning in detached part. Twinned where partial contact.	Lehoczky, <i>et al.</i> [87,88]
InAs <111>	Carbon-coated quartz	D = 9 mm L= 40-50 mm	Translated 11.3 mm/hr	Soak 2 hr	Salyut-6. Kristall.	Detached for 1/3 to 1/2 of length.		Khryapov, <i>et al.</i> [66,89-91]

InSb (10^{18} Te/cm ³) <111>B	Quartz. Graphite spacers at ends. 10 ⁻⁷ torr He	D = 14.5 mm L = 110 mm Feed 0.13 mm smaller diameter.	GF ~12 mm/hr	Heat up 120 min. Soak 60 min. Cool 70.2 K/hr for ~ 4 hr. Power off. Grew 60 mm	Skylab 3. Westinghouse GF. 1973	Same dia as feed with irregularly spaced ridges in growth direction, 25µm avg height. Irreg. spaced lines normal to growth direction, attributed to vibrations.	Concave interface. Diffusion-controlled seg'n with no fluct'ns. Striations on & near facet on one side. Twins normal to axis.	Witt, Gatos <i>et al.</i> [9,27,92- 95]
InSb (undoped & ~10 ²⁰ Sn/cm ³) <111>B	Same as above.	Same as above.	Same as above.	Same as above.	Skylab 3. Westinghouse GF. 1973	Same dia as ampoule. Smooth and shiny. Random gas bubbles.		Witt, Gatos <i>et al.</i> [27,92,93]
InSb (+ 10 ¹⁸ Te/cm ³) <111>B	Same as above.	Same as above.	~10 mm/hr, power off briefly, then ~17 mm/hr	Soak 60 min. Cool 70.2 K/hr for 140 min. Power off. Grew 60 mm	Skylab 4. Westinghouse GF. 1974	Reduced dia for 30 mm with irreg spaced lines normal to axis. Then irregularly spaced ridges ~ 25 µm high in contact.	Diffusion-controlled seg'n with no fluct'ns. Striations on and near facet. EPD 40% less. Twins normal to axis.	Witt, Gatos <i>et al.</i> [27,92,95]
InSb (undoped & ~10 ²⁰ Sn/cm ³) <111>B	Same as above.	Same as above.	Same as above.	Same as above.	Skylab 4. Westinghouse GF. 1974	Attached.		Witt, Gatos <i>et al.</i> [27,92,93]
InSb (10 ¹⁴ - 5 x 10 ¹⁷ Te/cm ³)	Carbon-coated quartz	D = 9 mm L= 40-50 mm	Translated 11.3 mm/hr	Soak 2 hr	Salyut-6. Kristall. ~ 1978	Detached 1/3 to 1/2 of length	EPD in detached regions ~2.5x10/cm ² (earth ≥ 5x10 ⁴ /cm ²). Striations.	Khryapov <i>et al.</i> [66,89-91]
InSb (undoped) <211>	Carbon-coated quartz. 10 ⁻⁷ torr	D = 8 mm L = 60 mm	Translated 11.3 mm/hr		Salyut-6. Kristall. ~ 1978	Contact only on oblong mounds (hillocks). Elsewhere matte.	EPD 250/cm ² . Particles mark seeding boundary. Many twins.	Khashimov <i>et al.</i> [96]
InSb (7x10 ¹⁷ Te/cm ³) <211>	Carbon-coated quartz. 10 ⁻⁷ torr	D = 8 mm L = 60 mm	Translated 11.3 mm/hr		Salyut-6. Kristall. ~ 1978	Spiral region free from contact, with hillocks & periodic bands, decreasing from 1/2 of perimeter to 1/5. Bubbles where attached.	Fewer grain boundaries, generally twins. No 5µm inclusions near seed as from earth. EPD 10 ³ -2x10 ⁵ /cm ² . Resist & mobility constant.	Khashimov <i>et al.</i> [96]
InSb (≤ 10 ¹⁶ Zn or ~10 ¹⁹ Te/cm ³) <111>B	Carbon-coated quartz. 10 ⁻⁵ torr	D = 13mm L= 20-30mm	GF 3 - 9 mm/hr	Soak 2.3 hr. G = 10K/cm. Cool 11.3 K/hr.	Salyut-6 - Soyuz. Splav-01. 1980.	One necked in for ~ 20 mm to ~ 1.5 mm maximum gap. Other necked in for ~ 16 mm.	Few inclusions, no striations. EPD reduced to ~100/cm ² .	Zemskov <i>et al.</i> [97-103]
InSb <111> B	Quartz. 10 ⁻³ - 10 ⁻⁴ torr	D = 13 mm L = 100 mm	GF	G = 10 - 15 K/cm. Cool 11.3 K/hr	Kosmos-1744. Splav-02. 1986	Necked in for ~ 10 mm. Highly asymmetric, ~ 3 mm gap on one side, < 1 mm on other.	No striations and enhanced perfection.	Zemskov [104,105]

InSb ($\sim 10^{16}$ Zn/cm ³) <111>	Quartz. $\sim 10^{-5}$ torr		GF	Heat 90 min, then power off.	Recoverable Satellite. Multi- purpose Crystal Processing Furnace. 1987	Smooth. Separated easily from quartz ampoule, while earth sample adhered tightly.	No striations. 3.6% radial variation in resistivity compared to 34% from earth.	Zhang <i>et al.</i> [106,107]
InSb (undoped & 9×10^{19} Sn/cm ³)	Quartz tube capped by graphite ends. With getters, $<4 \times 10^{-3}$ torr after exp't.	D = 10 mm. Machined increase to 14 mm part way down. L = 100 mm	0 to ~ 22 mm/hr, via calorimetric measure.	Soak 2 hr. Cool 4.3 hr.	D1 (Shuttle). Gradient Heating Facility. 1987	Attached except where rough from machining. Wide bubble over 22% at start of growth of Sn- doped, less on undoped. Detached part faceted.	Intensive segregation of Sn near bubble, attributed to Marangoni convection.	Duffar <i>et al.</i> [108-110]
InSb	Quartz and BN tubes with graphite & BN end caps.	D = 12 mm L = 15 mm		Cooled in ~ 100 s.	TEXUS 31 rocket (5 min). TEM01 Isothermal Furnace.	Kept shape of feed rods due to oxide coating, which was $\sim 1 \mu\text{m}$ thick & mostly Sb oxide.		Duffar <i>et al.</i> [39]
InSb	2 quartz & 2 BN tubes with C end caps. One each smooth, one with grooves. Vacuum (Ar).	D = 12 mm L = 15 mm		Cooled in ~ 100 s.	TEXUS 32 rocket (5 min). TEM01 Isothermal Furnace.	All detached. Smooth ampoules gave irregular & larger facets. Much more cylindrical in machined ampoules where ingot contacted the ridges.		Duffar <i>et al.</i> [39,43, 111]
InSb <111> B	Quartz. $10^{-3} - 10^{-4}$ torr	D = 13 mm L = 100 mm	GF	G = 10-15 K/cm. Cool 11.3 K/hr	Foton. Splav-02. 1989	Detached $\sim 1/2$ of length on one side, much less on other side.	No striations. Enhanced perfection	Zemskov [104]
InSb (three 7×10^{18} Te/cm ³ , three 3×10^{13} Cd/cm ³) <111>B	Quartz. Quartz piston and spring at end. 400 torr Ar.	feed rod: D = 4.42 mm L = 35 mm ampoule: D = 4.49 mm	GF ~ 4 mm/hr	Soak 2 hr at 750°C. Cool 30 K/hr. G ~ 52 K/cm	MIR. QUELD. 1996	Fully detached 0.5-6 mm, then 6-8 mm with 5- 10 μm high contact ridges. One sharp transition to attached attributed to "acceleration" event.	When full contact, nucleated new grains and EPD increased. Striations full length of Te-doped. Reduced axial segregation.	Redden & Mickleth't [47-49]
NaF-NaCl (eutectic; 21% NaF)	Graphite	D = 7.9 mm L = 64 mm	GF	Cool 36 K/hr. G = 50 K/cm	Skylab. Westinghouse GF. 1974	Detached.	Fewer faults, better optical transmission.	Yue and Yu [9,112, 113]
PbBr₂ (+ 2% PbCl ₂ , quartz particles)	Quartz. $\sim 10^{-5}$ torr		GF		TR-IA 3 rocket (6 min). 1993	Flattened bubbles yield microscopic free surfaces in places.	Rapid movement of particles attributed to Marangoni convection around flattened bubbles.	Kinoshita <i>et al.</i> [114-117]
PbTe (+ 0.41% In)	Quartz. 10^{-5} torr	D = 8 mm L ~ 30 mm	Translated 11.3 mm/hr	Heat up 90 min. Soak 4 hr. G ~ 90 K/cm	Salyut-6. Kristall.	Many pores for ~ 21 mm, especially on one side. Initial deep, irregular neck.	Concentration of In more uniform.	Abramov <i>et al.</i> [118,119]

PbTe (+ 10^{18} Ag/cm ³)	Quartz. 380-610 torr Ar	D = 17 mm L = 50 mm	GF 10 mm/hr	G = 30 K/cm. Cool 30 K/hr.	Spacelab-1 (Shuttle). CNES GF	Many bubbles up to 4 mm in diameter. No gap apparent on remainder.	Reduced axial segregation.	Rodot & Tottereau [120,121]
PbSe_{0.5}Te_{0.5}	Quartz		GF 2-50 mm/hr	Soak 2 hr (Syrena 1), 4 hr 45 min (Syrena 2)	Salyut-6. Splav-01. 1978	Detached	Quality strongly dependent on growth rate. At slow growth rates, grains ~5mm.	Galazka <i>et al.</i> [85]
Pb_{0.8}Sn_{0.2}Te	Quartz. Ar	D = 16 mm L ~ 40 mm	< 3.5 mm/hr	G = 20 K/cm	Shuttle STS 61A. 3-zone MEA furnace. 1985	Few small grains contacted the wall. Remainder detached with very small gap.		Fripp <i>et al.</i> [122,123]
Pb_{0.8}Sn_{0.2}Te <111>	BN. BN piston with graphite spring. <10 ⁻⁵ torr	D = 15 mm L = 58 mm	Translated 5.5 mm/hr. Grew 32 mm.	Heat up 1 hr. Soak 1 hr. G > 40 K/cm.	SL-J/FMPT (Shuttle) 1992	Part detached.	EPD 5x10 ⁵ /cm ² (earth 3x10 ⁶ /cm ²). Mobility & resistivity ~2x higher. Homogeneous in void- free part.	Kinoshita [116,117, 124,125]
PbSnTe	Quartz. 10 ⁻⁶ torr	D = 10 mm L = 77 mm	Zone melt at 2mm/hr for 4 hr		Mirror furnace.	Wavy surface. Slid out of ampoule easier.	77K mobility 3x larger. Composition almost constant.	Sohachi & Segawa [126]
Pb_{0.8}Sn_{0.2}Te			Translated	Soak 12-24 hr.	USMP-3&4 (Shuttle). Advanced Automat. Direct. Solid'n Furn. 1996 & 1997	Necked in for ~1cm from near initial growth. Many irregular trenches ~1mm deep.	Fully mixed axial concentration profile.	Fripp <i>et al.</i> [127-130]
Si (+ Sb or B)	Graphite or Mo. 10 ⁻⁵ torr	D = 8 mm	GF 420 - 600 mm/hr	100 s to heat. 80 s to melt. 400 s to freeze	Mir rocket (10 min). BKT exothermic furnace. 1980	Contacted walls only in separate small areas.	Single crystals (polycryst from earth). Surface enriched in Sb. EPD 10 ² -10 ³ lower.	through Avduevsky [68]
Te	Quartz. Vacuum.	feed rod: D ~ 5 mm L ~ 70 mm ampoule: D ~ 6 mm	GF		MIR. Crystallizator CSK- 1 1996	One sample completely detached, two others partially. All easily removed from ampoule.	Mobility of completely detached crystal equal to record for crystals grown on earth.	Parfeniev <i>et al.</i> [131]
Zn (+ Zn ⁶⁵)	Graphite. 5x10 ⁻⁶ torr Ar	L = 46.8 mm	GF	Soak 1 hr at 775°C. G 45 K/cm	Skylab 3. Westinghouse GF. 1974	Wrinkled surfaces on hotter end.	Nonuniform distribution of isotope. 50X lower diffusion coefficient.	Ukanwa [9,132]
Zn - Pb -Bi (11 alloys of different comp'n)	Graphite	D ~ 7 mm L ~ 40 mm		Soak 15 min ~850°C. Cool ~1800 K/hr	D1 (Shuttle). Isothermal Heating Facility. 1985	Gap on cold side with small Zn droplets protruding through surface. Wavy surface on parts of some samples.	Cavity in center.	Ahlborn, Lohberg [133,134]

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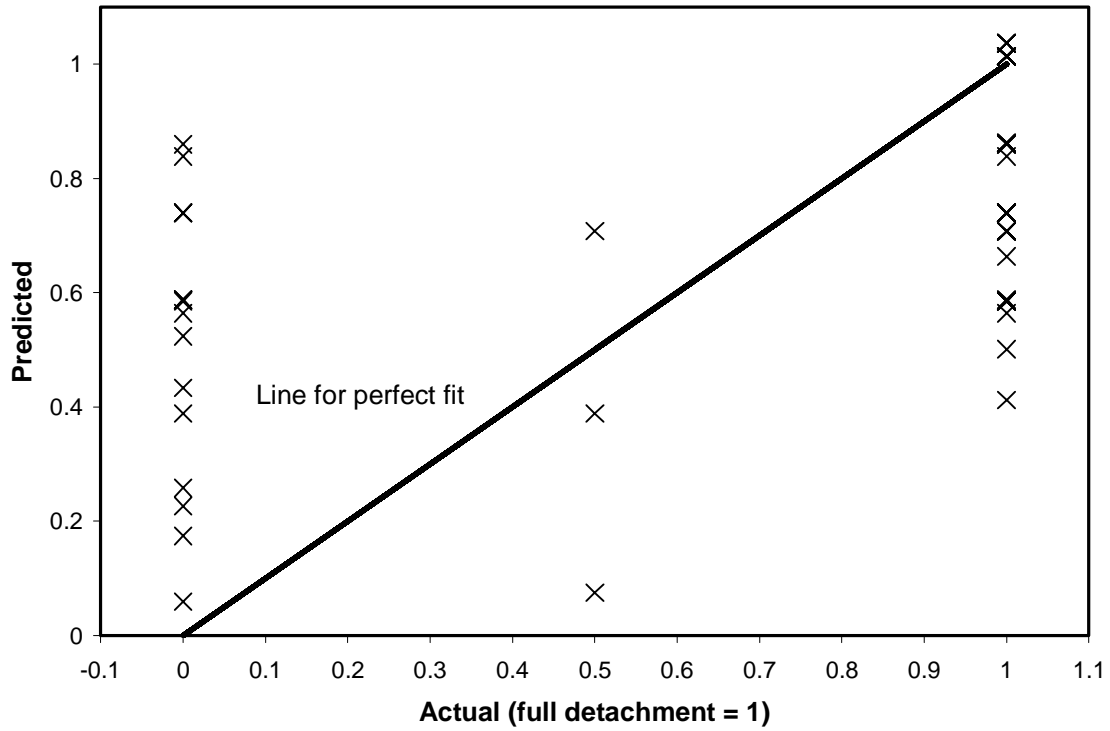


Figure 1. Detached solidification predicted from the correlating equation 1, versus observed detachment. The value is 1 when detachment occurred according to the criteria in modes 5 or 6 in section 1, 0.5 when mode 4 was observed, and 0 for attachment.