N91-12403

4. DESIRABLE LIMITS OF ACCELERATIVE FORCES IN A SPACE-BASED MATERIALS PROCESSING FACILITY

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(The editors of this Proceedings Report compiled the following synopsis of Dr. Naumann's presentation, based on tape recordings taken during his talk).

There are three categories of accelerations to be encountered on orbiting spacecraft: (1) quasi-steady accelerations, caused by atmospheric drag or by gravity gradients, 10^{-6} to 10^{-7} g_o; (2) transient accelerations, caused by movements of the astronauts, mass translocations, landing and departure of other spacecraft, etc.; (3) Oscillary accelerations, caused by running machinery (fans, pumps, generators) (Figure 1).

Steady accelerations cause continuing displacements; transients cause time-limited displacements (Figure 2). The important aspect is "the area under the acceleration curve, measured over a certain time interval." (Note that this quantity is not equivalent to a velocity because of friction effects!)

Transient motions are probably less important than steady accelerations because they only produce constant displacements. If the accelerative forces were not equal and opposite, the displacement would increase with time. A steady acceleration will produce an increasing velocity of a particle, but eventually an equilibrium value will be reached where drag and acceleration forces are equal. From then on, the velocity will remain constant, and the displacement will increase linearly with time.

STEADY ACCELERATIONS:

ATMOSPHERIC DRAG: $2 \times 10^{-8}\ g_o - 2 \times 10^{-6}\ g_o$ (DEPENDING ON SOLAR CYCLE)

GRAVITY GRADIENT: $3.6 \times 10^{-7}\ g_o$ FOR EACH METER ABOVE OR BELOW C/M

TRANSIENT ACCELERATIONS:

REBOOST THRUSTERS:	0.0018 m/sec = $1.8 \times 10^{-4}\ g_o$ - sec (FEW MINUTES EVERY 90 DAYS)
ATTITUDE CONTROL THRUSTER:	$4.2 \times 10^{-4}\ g_o$ - sec (EVERY 2,100 sec FOR 5-deg DEAD-BAND) $2.0 \times 10^{-4}\ g_o$ - sec (EVERY 1,000 sec FOR 1-deg DEAD-BAND)
CREW MEMBER TRANSLATING AT 2.5 m/sec	$2 \times 10^{-4}\ g_o$ - sec (DURATION 1 TO 4 sec)
200-kg MASS TRANSLATING AT 1 m/sec	$1.7 \times 10^{-4}\ g_o$ - sec (DURATION 10 TO 100 sec)

OSCILLATORY ACCELERATIONS:

CREW MEMBER NODDING HEAD	$3 \times 10^{-5}\ g_o$ AT 1 Hz
ROTATING MACHINERY:	$3 \times 10^{-6}\ g_o$ AT 30 Hz (MORE SEVERE LOCALLY)
STRUCTURE FLEXING FROM CREW MOTION:	$2 \times 10^{-3}\ F_o\ g_o$ ($T_{IMPULSE} << 1/F_o$)

FIGURE 1. SUMMARY OF RESIDUAL ACCELERATIONS

FREE PARTICLE IN 10-cm-RADIUS CONTAINER, $X = \dot{X} = 0$ AT $t = 0$

ATMOSPHERIC DRAG, $g = 2 \times 10^{-7}\ g_o$; $t_{WALL} = 300$ sec

WORST-CASE G- GRADIENT, $g = 10^{-5}\ g_o$; $t_{WALL} = 45$ sec

TRANSIENT FROM THRUSTER, $gt = 2 \times 10^{-4}\ g_o$ - sec; $t_{WALL} = 50$ sec

TRANSIENT FROM CREW MOTION OF 10 m; $X_o = 0.6$ cm

TRANSIENT FROM 200-kg MASS OF 100 m; $X_o = 16.7$ cm, $t_{WALL} = 60$ sec

JITTER FROM HEAD MOVEMENT; $X_o = 8$ μm AT 1 Hz

JITTER FROM ROTATING MACHINERY; $X_o = 8$ nm AT 30 Hz

JITTER FROM STRUCTURE FLEXING; $X_o = 500$ μm/F_o AT F_o Hz

FIGURE 2. EFFECT OF RESIDUAL ACCELERATIONS ON FREE PARTICLE IN A BOX

In a transient mode of acceleration, the displacement will be constant if the accelerative force acts only in one direction. If the transient is oscillatory, the displacement goes back to zero after the transient. In all practical cases, a residual displacement should be expected because of non-linearity effects.

If a box with a free-floating particle were exposed to a drag force of 10^{-7} g_o, and if the initial distance between particle and box wall were 5 cm, the particle would hit the wall after about 300 sec. If the accelerative force were 10^{-5} g_o, the time would be 30 sec. With a thruster transient, it will hit the wall in 50 sec. A transient from crew motion will simply offset the particle by about 0.6 cm. Moving a 200 kg mass over a distance of 100 meters will bang the particle into the wall because its net displacement will be some 16 cm.

Nodding of an astronaut's head at 1 hertz produces an oscillating acceleration in the Space Station of about 10^{-5} g_o. Rotating machinery will cause particle displacements on the order of 8 nanometers. The natural frequency of Space Station structural flexing will be a few tenths of a hertz.

As an example, a protein crystal of 0.5-mm diameter, suspended in a 5-mm drop of water, would remain floating for 5 days if exposed to a steady acceleration of 3×10^{-7} g_o. A 1-cm crystal in a 10-cm vial under 10^{-5} g_o would take 2.5 hours before it hit the wall (Figure 3).

Transient effects, such as caused by astronauts nodding their heads, are mild. They may cause problems in float zone experiments, but they can be avoided by mechanical or magnetic vibration isolation.

"Steady accelerations can really kill you in a lot of processes."

The settling times of suspensions are controlled by the competing effect of Brownian motion and gravitational acceleration (Figure 4). Latex spheres of 0.2 micron diameter will remain suspended indefinitely even under 1 g_o (Figure 5). Blood cells require an acceleration level as low as 10^{-6} to 10^{-7} g_o to remain suspended. A mixture of molten lead

TYPE OF DISTURBANCE	CASE I	CASE II
AERODYNAMIC DRAG (2×10^{-7} g_o)	$\dot{X} = 0.048$ cm/day $t_{WALL} = 5.2$ DAYS	$\dot{X} = 19$ cm/day $t_{WALL} = 6.3$ hr
GRAVITY GRADIENT (WORST CASE) (1×10^{-5} g_o)	$\dot{X} = 2.4$ cm/day $t_{WALL} = 2.4$ hr	$\dot{X} = 960$ cm/day $t_{WALL} = 7.5$ min
THRUSTER FIRING (2×10^{-4} g_o - sec)	$\Delta X = 33$ μm	$\Delta X = 1.3$ cm
CREW TRANSLATION (10 min 4 sec)	$\Delta X = 33$ μm $\rightarrow 0$	$\Delta X = 1.3$ cm $\rightarrow 0.71$ cm
200-kg MASS TRANSLATION (100 min 100 sec)	$\Delta X = 28$ μm $\rightarrow 0$	$\Delta X = 1.1$ cm $\rightarrow 0$
JITTER FROM HEAD MOVEMENT	$\Delta X = \pm 80$ nm	$\Delta X = \pm 7$ μm
JITTER FROM MACHINERY	$\Delta X = \pm 0.8$ nm	$\Delta X = \pm 0.8$ nm
JITTER FROM STRUCTURE	$\Delta X = 50$ μm, $F_o < 10$ Hz $\Delta X = 500/F_o$ μm, $F_o > 10$ Hz	$\Delta X = 2.1$ cm, $F_o < 0.02$ Hz $\Delta X = 0.05/F_o$ cm, $F > 0.02$ Hz

CASE I: 0.5-mm-DIAMETER PROTEIN CRYSTAL IN 5-mm DROPLET, $\Delta\rho = 0.2\ \rho$, $\nu = 10^{-2}$ cm^2/sec

CASE II: 1-cm-DIAMETER CRYSTAL IN 10-cm-DIAMETER CONTAINER, $\Delta\rho = 0.2\ \rho$, $\nu = 10^{-2}$ cm^2/sec

FIGURE 3. EFFECTS OF RESIDUAL ACCELERATION ON PARTICLE IN VISCOUS MEDIUM

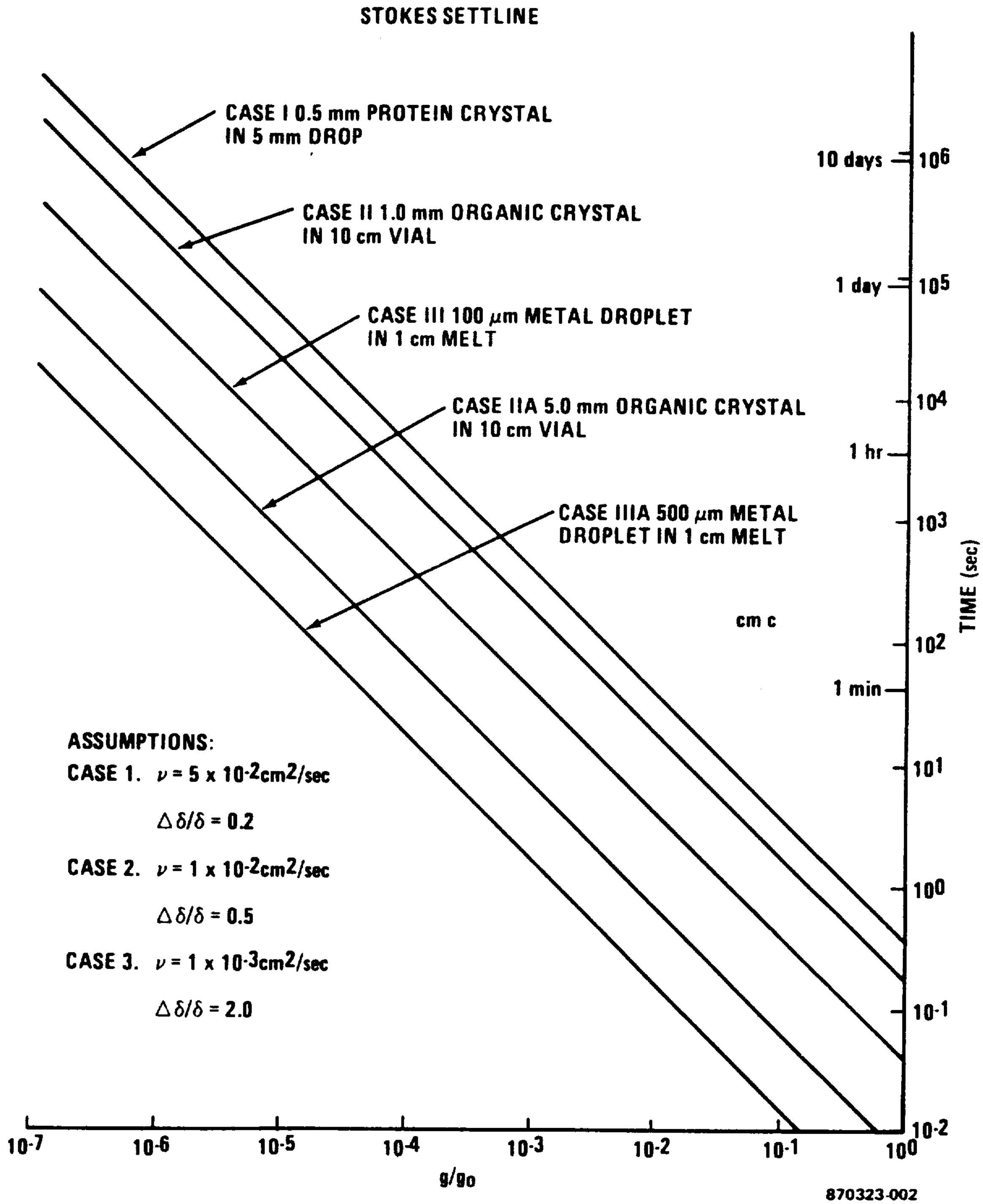


FIGURE 4. STOKES SETTLING

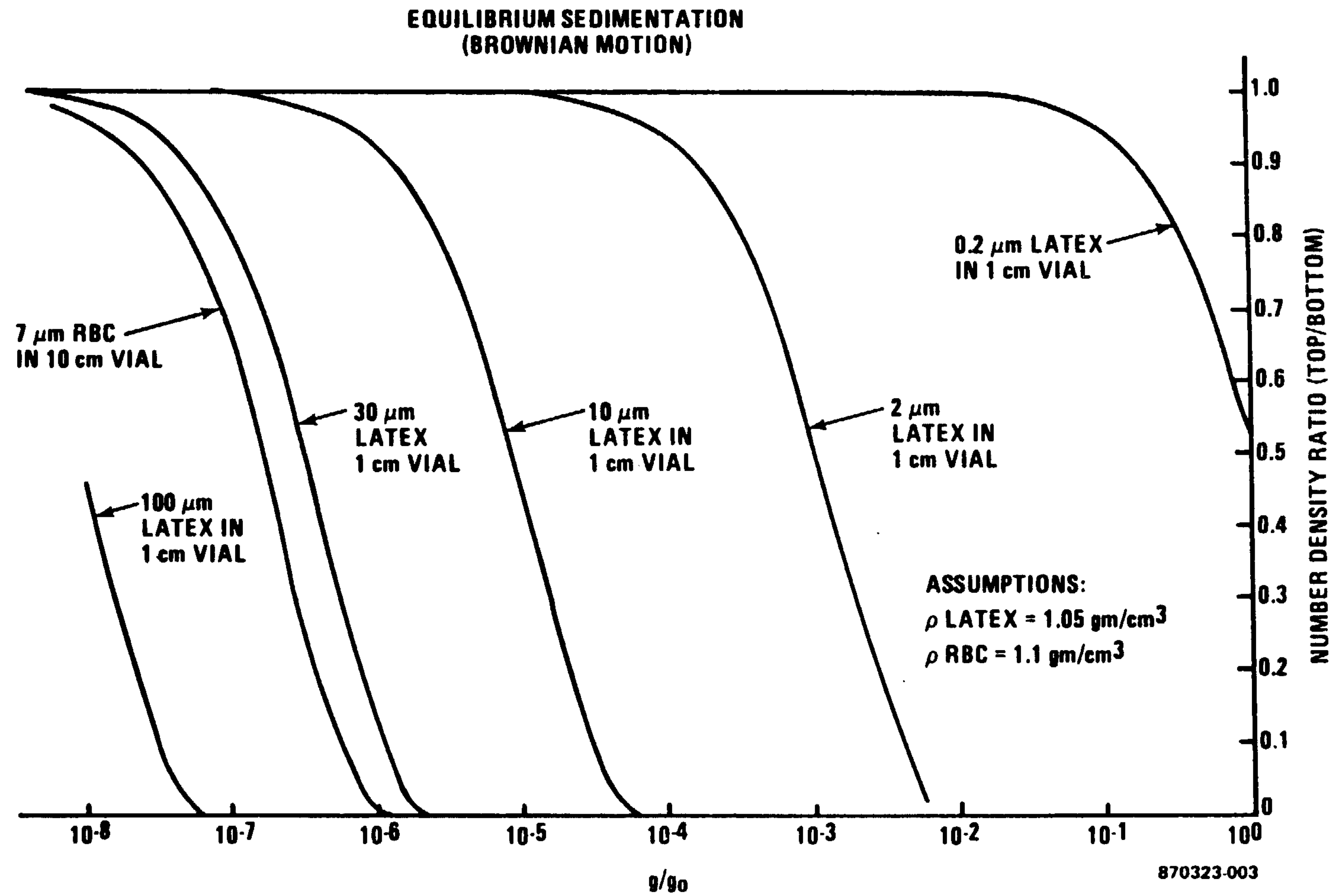


FIGURE 5. EQUILIBRIUM SEDIMENTATION (BROWNIAN MOTION)

and tin will remain homogeneous even at 10^{-6} g_o only when the mixture ratio tin:lead is smaller than 3.5 to 4% (Figure 6).

This latter case has been analyzed by Stan Coriell at the Bureau of Standards; it is an example of a situation in which the solution gradient is unstable, and the thermal gradient is stable ("double-diffusive convection").

If a crystal grows in a solution, the transport of material is influenced by diffusion and by convection. Under reduced gravity conditions, convection effects are reduced, diffusion effects are not. In the diagram of Figure 7, the line divides the regions where convection (above) or diffusion (below) is predominant.

The Peclet number measures the convective transport as compared to the diffusive transport. For the thermal case, it is defined as the characteristic velocity, v, times the characteristic length, ℓ, divided by the thermal diffusivity. At thermal Peclet numbers below ℓ, thermal fluctuations are suppressed. To suppress compositional fluctuations, solutal Peclet numbers must be kept below ℓ. Solutal Peclet numbers contain the chemical instead of the thermal diffusivity.

Substituting proper numbers in the Peclet expressions, the thermal Peclet number turns out as 10^2 g_o ℓ^3, and the solutal Peclet number as 10^6 g_o ℓ^3, for 1-cm samples. This means that accelerations must not be greater than 10^{-9} g_o if 10-cm samples without detrimental solutal convection effects are to be produced. Such a low level of gravitational acceleration cannot be attained on a space vehicle in low earth orbit. If the growth solution is a conductive medium, application of a magnetic field would greatly reduce diffusion - controlled convection. Experiments with magnetic fields have been carried out in ground-based labs.

Figure 8 was taken from a paper by Chang and Brown who analyzed the radial segregation in crystals grown by the Bridgman-Stockbarger

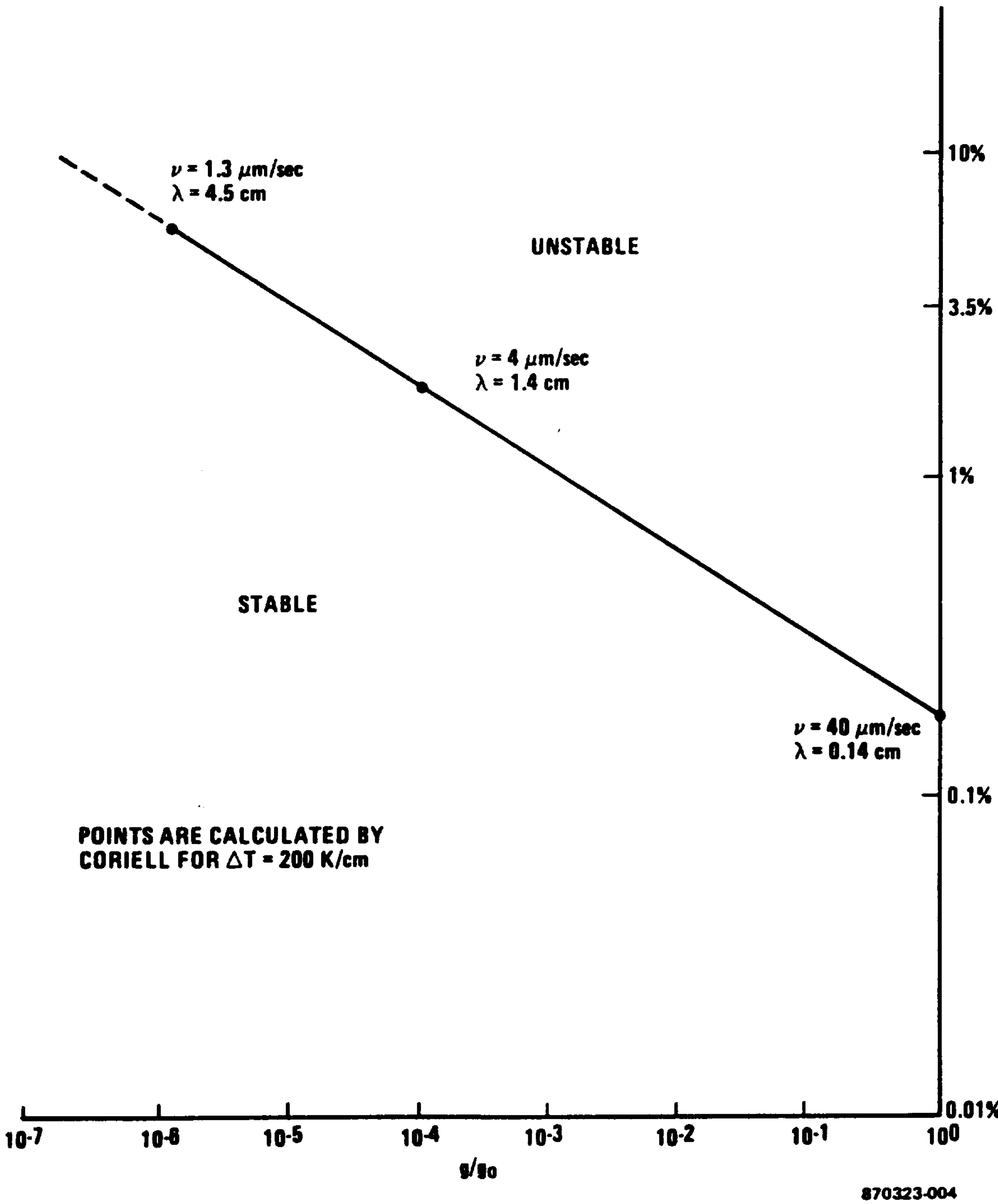


FIGURE 6. DOUBLE-DIFFUSIVE CONVECTION (Sn in Pb)

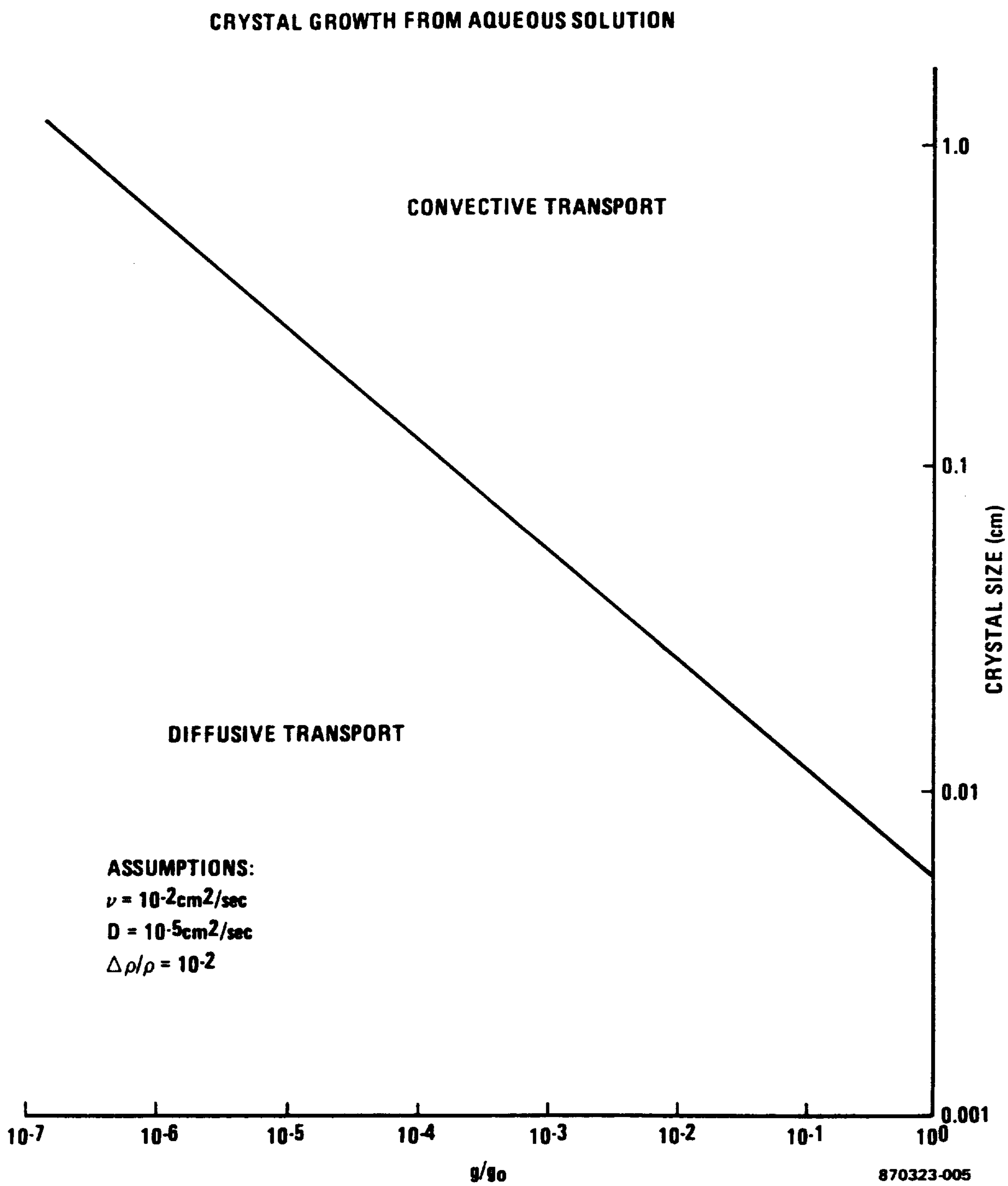


FIGURE 7. CRYSTAL GROWTH FROM AQUEOUS SOLUTION

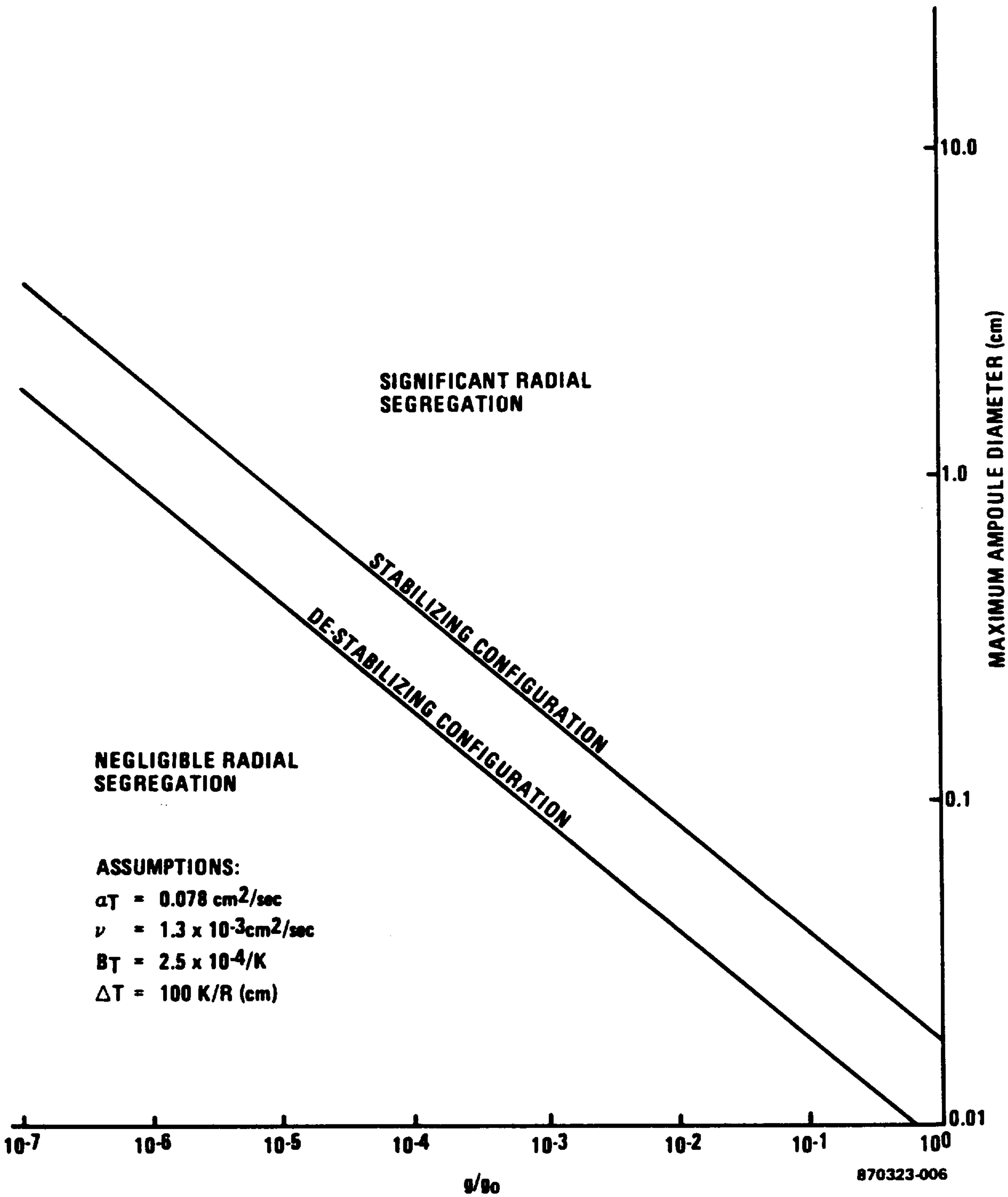


FIGURE 8. BRIDGMAN - STOCKBARGER GROWTH (FROM CHANG & BROWN)

method. Significant radial segregation occurs above the upper line and is absent below the lower line. For a one-centimeter sample, acceleration levels must not exceed 10^{-5} or 10^{-6} g_o if diffusion-controlled flow is to be maintained. To grow larger crystals, far lower levels will be needed. This might be achieved, in the case of conductive melts, by forcing a magnetic field on the system. Figure 9 shows the reduction of convective flow velocities as a function of magnetic field strength and electric conductivity of the melts. Crystals of less than 1 cm diameter can be grown under diffusion-controlled conditions without a magnetic field. To grow crystals up to about 10 cm requires only a fairly modest magnetic field, but strong fields will be needed for larger crystals.

Question (Reg Berka, JSC): Do all these curves refer to steady-state accelerations? How would transients and periodic accelerations affect these charts?

Naumann: If the transient is short as compared to the response time of the fluid, an average value of the acceleration should be taken. The response time of the fluid is on the order of the diffusive coefficient divided by the square of the length scale.

"We have reasons to believe that on Spacelab 3 steady state accelerations were on the order of 10^{-7} g_o, substantially better than Space Station specifications. We believe that a level of 10^{-5} g_o, specified as a requirement for the Space Station, is way too high. With the new configuration of the Space Station where the line of the center of mass will be located within the lab module, steady accelerations will be much better than 10^{-5} g_o." (Note that this statement refers only to steady state accelerations, but not to transient and oscillating accelerations.)

If steady state accelerations on the Space Station are not kept near 10^{-7} g_o, crystals that can be grown on the Space Station will be severely limited in size. "We think that would be a fatal error ...

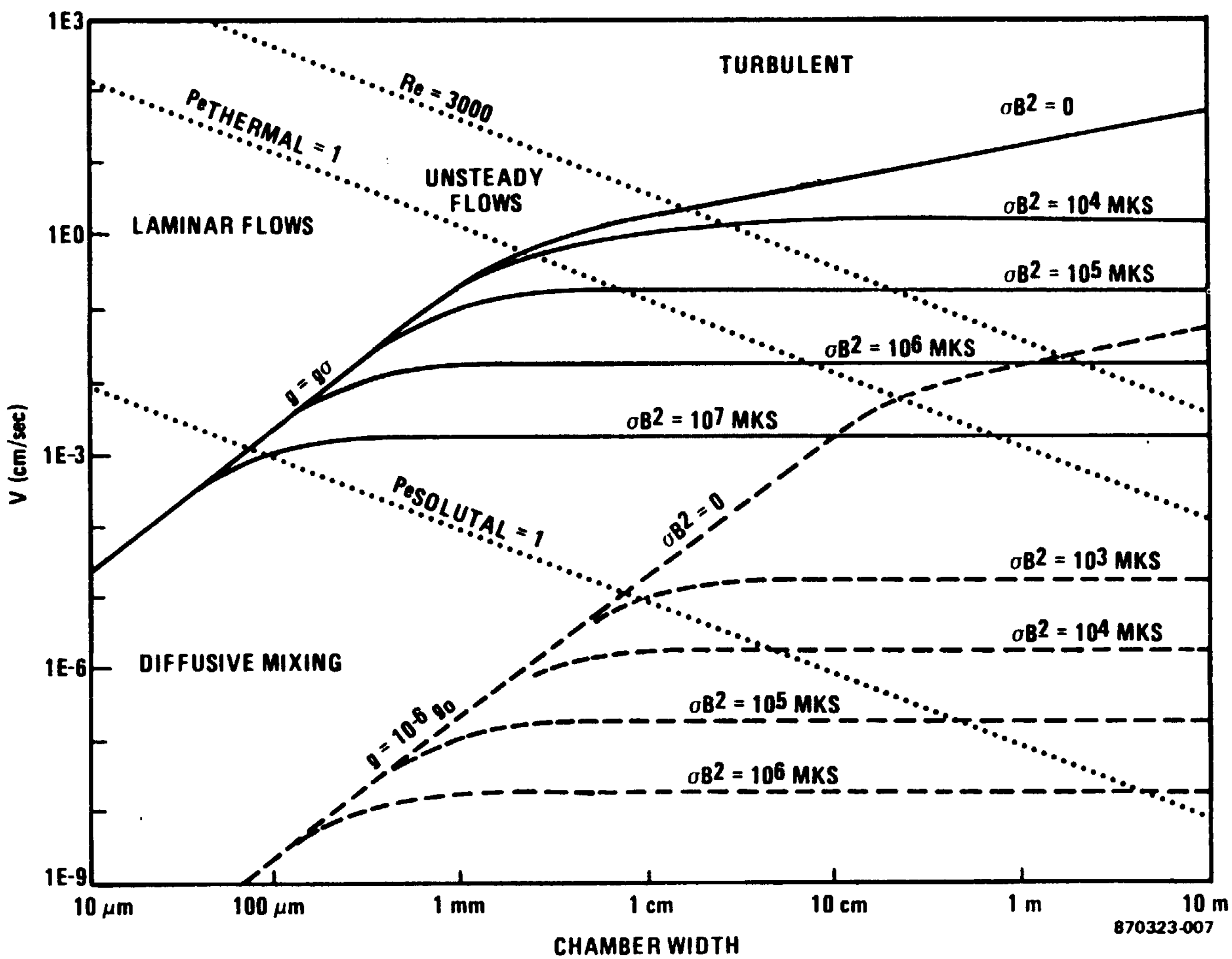


FIGURE 9. CONVECTIVE FLOW VELOCITY AS A FUNCTION OF MAGNETIC FIELD STRENGTH, ELECTRIC CONDUCTIVITY, AND CHAMBER SIZE, AT VARIOUS GRAVITATIONAL ACCELERATIONS

unless we can find industries that are willing to accept crystals of less than 1 cm in size, which I think is unlikely, you really don't have an industrial constituency ... As far as accelerometer development goes, those are the accelerations we really want to measure. I'm not sure that measuring peak accelerations is the right thing to do; I think the more useful thing to do would be to measure the acceleration x time product, over varying time intervals."

Question (Larry Collins, Alabama A&M University): What are the units for the magnetic field expression?

Naumann: The units are the product of sigma times B squared, in MKS units; sigma being the conductivity in siemens (mho-meters), and B is measured in tesla. The strongest fields would be 10^5 or 10^6 tesla.

Question: (Not understandable)

Naumann: There is a very nice paper by Bob Dreslin who was at NASA Headquarters, which gave the closed form solution of the flow of a fluid in a circular container when a thermal gradient is present. A brief overview of flow conditions when thermal gradients are present is shown in Figure 10.

Question: How can a measured profile of acceleration versus time be applied to the diagram that shows "acceptable" and "desirable" acceleration versus frequency?

Naumann: You first take the acceleration profile and decompose it into the three coordinate components. Then, you decompose each of these profiles into its Fourier components; this will give you an amplitude versus frequency plot. If this measured amplitude versus frequency plot is below the lines in the diagram, you are in good shape. (Note that this analysis is not without problems, as pointed out quite drastically by Ken Demel; see "Summary of Workshop," p. 28-3).

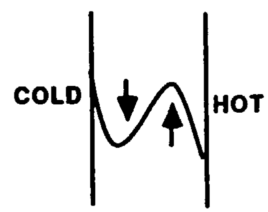
Question (Fred Henderson, Teledyne Brown): The experimenters of the French Mephisto experiment have requested an accelerometer sensitive

Must keep $Pe_{Thermal} = \frac{\hat{v}L}{\alpha}$ $<<1$ to suppress thermal fluctuations

Must keep $Pe_{Solutal} = \frac{\hat{v}L}{D}$ $<<1$ to suppress compositional fluctuations

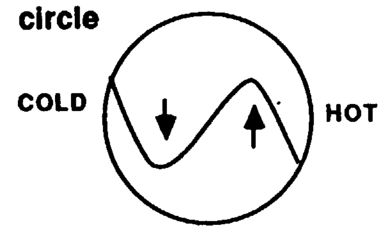
To estimate $\hat{v}$ for steady acceleration, consider 2-D flow in:

a. channel



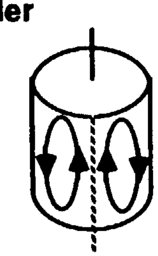
$$\hat{v} = \frac{\beta g \, \Delta T \, L^2}{72\sqrt{3}\, v}$$

b. circle



$$\hat{v} = \frac{\beta g \, \Delta T \, R^2}{48\sqrt{3}\, v}$$

c. cylinder



$$\hat{v} = \frac{\beta g \, \Delta T \, R^2}{48 \, v}$$

For $\beta = 10^{-4}$, $g = 10^{3} g_o$, $\Delta T = 10k$, $v = 10^{-3}\ cm^2/sec$

$$\hat{v} \approx \frac{10^{-4} \times 10^{3} g_o \times 10}{10^{2} \; 10^{-3}} \, L^2 = 10 \, g_o \, L^2 \ (cm/sec)$$

For $\alpha = 10^{-1}\ cm^2/sec$, $D = 10^{-5}\ cm^2/sec$

$Pe_{Thermal} = 10^{2} g_o L^3$, $Pe_{Solutal} = 10^{6} g_o L^3$

FIGURE 10. ESTIMATE OF REQUIRED G-LEVELS

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to 10^{-4} g_0 at 100 Hz, and they had a theoretical argument for this request. Are you familiar with their rationale?

Naumann: I really don't know why they specified that high a frequency. They said that's what they need, and we just accepted it. They may know something we don't know, or we may know something they don't.

Question (Byron Lichtenberg, Payload Systems Inc.): I would like to refer to your earlier statement about an astronaut nodding his head. Your assumption was for a 5 kilogram mass coupled to a rigid body giving a 20 micro-g acceleration. The assumption is that a person's head is a 5 kg mass driven by an electric motor and rigidly coupled to the floor. In reality however there is a considerable amount of fluid damping.

Naumann: Yes, that's what I assumed; a rigid body coupled to the floor. Then I realized later that if you hold something in your hand, and if you move it with a displacement of 10 centimeters at a frequency of 1 Hz, that will be equivalent to 0.1 g_0. Thus it is very difficult to move things around by hand and not to exceed large acceleration levels.

Ken Demel, JSC: But analysis will show that this is less of a problem than it would be if it were a steady state acceleration.

Question: Have magnetic suspensions and other isolating mechanisms been considered for use on the Space Station?

Naumann: There are a number of suspension systems available, both mechanical -- using airbags or springs with dashpots -- and magnetic, that isolate the region of the experiment from the main structure. They will isolate an experiment on a spacecraft from transient and oscillatory motions. But there are limits to how far you can go. The major limit will be the amount of free travel of the isolated platform relative to the rest of the spacecraft. Theoretically, you could keep the experiment totally suspended and fly the spacecraft around it if you were free to move the center of mass of the spacecraft, but that would be rather difficult to accomplish. You could keep the accelerative forces transmitted to the experiment absolutely zero if you had a large enough free space around it ... In practice, you could probably isolate very well down to 10 Hz, maybe 1 Hz or even 0.1 Hz. However, lower frequencies you would not be able to isolate within a reasonable structure.

Question (Ed Bergmann, C. S. Draper Laboratory): Isolating the motion is not at all that impossible, as Owen Garriott will discuss later. I just wanted to mention that it has actually been done; there have been some simulations where the orbiter was flown around an experiment.

Naumann: Oh yes, but that assumes that the spacecraft is maneuverable; unfortunately, the Space Station is not.

Question: I don't understand why you are not concerned with jitter.

Naumann: The question is: would jitter effects produce microscopic motions at the interface that could cause problems? The answer is: yes, they probably could. I think we need to be concerned about it. I'm less concerned about it because I can do something about it if I need to; I can isolate.

The macroscopic effects, such as the influx of fluid of a different concentration to the interface of a growing crystal, can really mess up diffusion-limited growth. This is a first-order effect, and it is more worrisome than the second-order effects caused by jitter. The latter may consist of the displacement of an element of fluid by a few microns over the interface. We don't really know what consequences that may have. We have not studied that yet, and I would say that this is probably a second-order effect. I would be concerned about it only after the first-order problem has been solved.

Table 1 lists a number of conclusions regarding low-acceleration work on the Space Station.

TABLE 1. CONCLUSIONS

- Spacelab module contains the center of mass of the system. Measured steady accelerations are 3.8×10^{-7} g_0 at the FES.

- A steady acceleration level of 10^{-5} g_0 presently specified for Space Station is 26 times worse than we have now and will limit the usefulness of Space Station as a national microgravity facility.

- The most serious consequence will be the size of electronic-electro-optical materials and aligned in situ composite alloys that can be grown without significant gravity effects. This will greatly restrict commercial interest.

- Examples:

  - Uniform doping can only be achieved in Bridgman-grown crystals up to 0.8-cm diameter.

  - Alloy compositions will be limited to a few percent (3 wt % for Sn in Pb unless diameter << 2.5 cm).

  - Diffusion-controlled transport cannot be maintained for solution-grown crystals larger than a few millimeter diameter (3.3 mm for triglycine sulphate).

  - Rotation will be needed to maintain free suspensions, even for 0.5-mm protein crystals.

- Access to the vicinity of the flight path of the center of mass is needed to provide the same steady-state accelerations presently available on Spacelab.

- Tolerance to transient or periodic accelerations increases as ω^2. Additional attenuation can be obtained by shock mounting or by active isolation control.

- Additional development is needed to reduce effects of steady or very low frequency distrubances.

  - Possibly experiment rotation and/or magnetic damping.