N91-12404

5. IMPLICATIONS OF ACCELERATION ENVIRONMENTS ON SCALING MATERIALS PROCESSING IN SPACE TO PRODUCTION

Ken Demel, NASA/Johnson Space Center

I will cover some considerations regarding materials processing from a commercial perspective. There's a lot of science and research involved, but I think that the product potential in the commercial sector will ultimately pull the research and science programs along to benefit mankind in keeping with the NASA charter. The best mechanism we have for dispersing scientific results of these programs to mankind in general is through a process called commercialization. Like it or not, that's our best distribution system. I represent Space Station Level B and have been working with the commercial advocacy group. We are starting from a perspective that had been pronounced by President Reagan in his state of the union addresses, and we're also considering the amendment to the Space Act in Public Law 98-361 given on the bottom of Figure 1. The amendment says that while you're doing things for all mankind, for national security, and domestic welfare, encourage commerce also. This is essentially the charter that we've taken for developing a commercial perspective that includes materials processing in space. Figure 2 indicates a number of commercial utilization areas that have been developed. The communications industry is well advanced. There is activity in earth and ocean remote sensing as well. The bottom of the figure indicates the promising area that we're here to discuss, and the commercial requirements regarding materials processing that are driving the Space Station design. Several key areas include power, proprietary data, operational requirements (including logistics), and also the center of gravity (c.g.) location, and control of that location with respect to materials processing payloads. The previous speaker, Bob Naumann, talked about small samples, whereas I am going to go through a rationale that says why you have to be even more careful as you expand the scale and go to larger samples.

Executive and Legislative Pronouncements

"We will soon implement a number of executive initiatives, develop proposals to ease regulatory constraints, and with NASA'S help, promote private sector investment in space"

State of the Union Address, 1984

"In the zero gravity of space, we could manufacture in 30 days life saving medicines it would take 30 years to make on earth. We can make crystals of exceptional purity to produce super computers. Creating jobs, technologies and medical breakthroughs beyond anything we ever dreamed possible."

State of the Union Address, 1985

The Congress declares that the general welfare of the United States requires that the National Aeronautics and Space Administration seek and encourage, to the maximum extent possible, the fullest commercial use of space."

Public Law 98-361 (Ammendment to Space Act of 1958)

Figure 1.

COMMERCIAL UTILIZATION

- SPACE IS ALREADY COMMERCIALIZED: COMMUNICATIONS INDUSTRY

- ENCOURAGING PRIVATE SECTOR IN SPACE IS PART OF U. S. NATIONAL SPACE POLICY AND PART OF NASA's STATUTORY MANDATE

- SEVERAL NASA ACTIVITIES HAVE A COMMERCIAL DIMENSION:
  - -- EXPENDABLE LAUNCH VEHICLES
  - -- LANDSAT
  - -- SPACE STATION
  - -- UPPER STAGES
  - -- NASA/INDUSTRY RESEARCH

- A SPACE STATION COULD PROVIDE LABORATORY AND SERVICING CAPABILITIES TO PRIVATE SECTOR'S ENDEAVORS IN SPACE

- SPACE STATION PLANNING INCLUDES:
  - -- COMMERCIAL WORKING GROUP
  - -- CONTRACTOR OUTREACH TO NON-AEROSPACE INDUSTRIES
- ONE PARTICULARLY PROMISING AREA: MATERIALS PROCESSING

- COMMERCIAL REQUIREMENTS INFLUENCE SPACE STATION DESIGN:
  - -- POWER
  - -- PROPRIETARY DATA
  - -- OPERATIONAL REQUIREMENTS
  - -- CG LOCATION & CONTROL WITH RESPECT TO MPS PAYLOADS

Figure 2.

We are aware of the "Why Materials Processing in Space" (Figure 3). Generally it is to apply another method of controlling the outcome of an experiment with a material. Every time a new process parameter has been added to our repertoire in processing materials there has been a great advance in materials capability. Progress, technological and otherwise, marches on materials capability, so it is for the reasons given here that we think materials processing could have a dramatic payoff. Buoyancy, sedimentation, and hydrostatic pressure and their adverse effects are well documented in the literature.

Figure 4 gets to the heart of the issue from the commercial standpoint. To determine whether one wants to enter a commercial enterprise, one does market surveys and finds out what he has to make to give himself a niche in the market for a consumer base. That dictates the size of the product to support his application market as indicated in the upper left hand corner of Figure 4. That in turn drives his space station resources, dictates his demand for resources, and his production rate and logistics flow that has to be implemented to maintain a market so that he can stay in business. Both the size of the product and the production rate drive factory investment requirements, and all that (market demand and production management) determines whether there is a positive return on investment. And if that little block, Return on Investment (ROI), doesn't come out right, he's not a participant. He can't afford to be. He is doing it on his own money. It's going through this sort of a model that leads to the issues shown in Figure 5, "Product Mortality versus Cost".

In Figure 5, the commercial endeavor starts out with the same process that experimenters start with, that is, science and research. It goes through a number of development sequences, then through engineering, and finally into production. While the venture capital is going at risk, as shown on a log scale, the objective is ROI past the break-even point on the far right in an appropriate time. Getting through those detailed steps of going from the possible approaches on

WHY MATERIALS PROCESSING IN SPACE?

"MICROGRAVITY" ENVIRONMENT ADDS NEW DIMENSION TO PROCESSING AND PROCESS CONTROL
- A NEW UNIQUE PROCESS PARAMETER

- BUOYANCY-DRIVEN CONVECTION DISAPPEARS
  - DIFFUSION CONTROL IS DOMINANT
  - UNWANTED MIXING IS ELIMINATED
  - THERMAL AND COMPOSITION FLUCTUATIONS VANISH

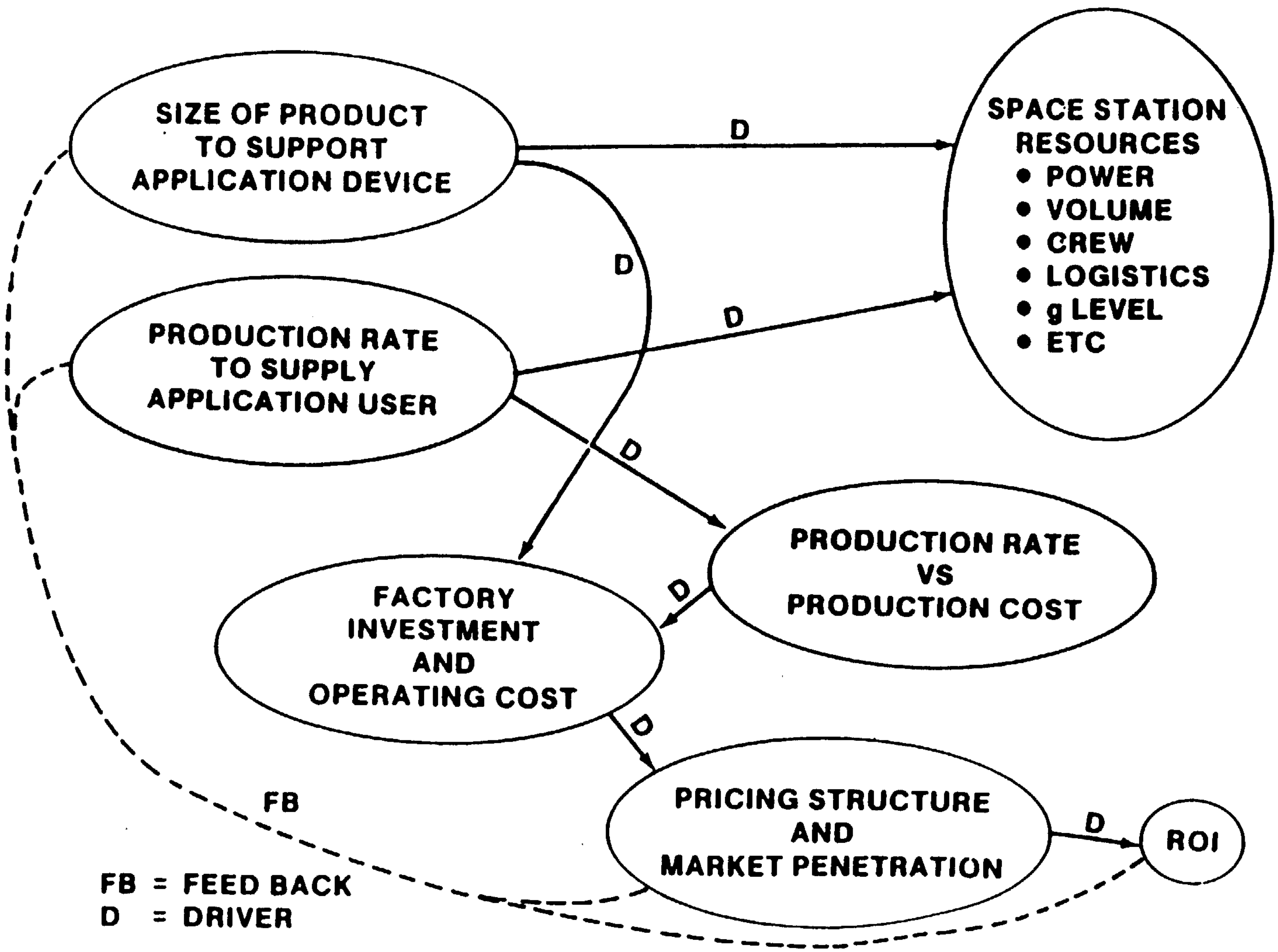
- SEDIMENTATION CEASES
  - HETEROGENEOUS SUSPENSIONS ARE MAINTAINED
  - MATERIAL PHASE MIXTURES ARE LONG LIVED
  - PROCESS BATCHES CAN BE CONTAINERLESS

- HYDROSTATIC PRESSURE GOES TO ZERO
  - LIQUIDS ARE SHAPED BY SURFACE TENSION
  - FLOAT ZONE PROCESSING AT LOW SURFACE TENSION

BONUSES - ULTRA HIGH VACUUM, HIGH PUMPING SPEED, HIGH HEAT REJECTION

Figure 3.

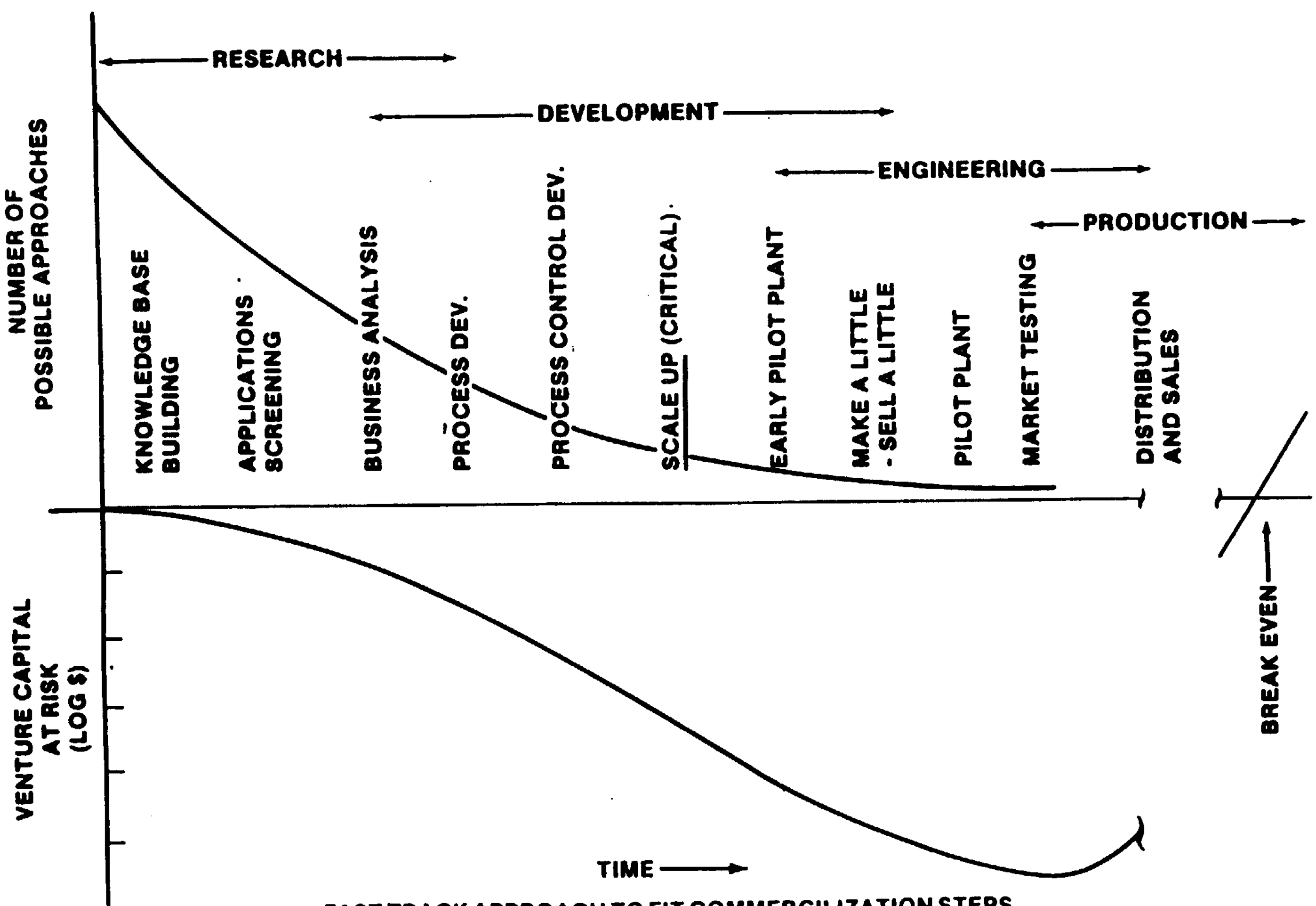
SCALING ISSUES VS MARKET DECISION



FB = FEED BACK
D = DRIVER

Figure 4.

PRODUCT MORTALITY VS COSTS



FAST TRACK APPROACH TO FIT COMMERCILIZATION STEPS
WITHIN CORPORATE HORIZONS

Figure 5.

the left to a final product and output on the right, leads the commercial endeavor through a number of hurdles. Knowledge base building and a certain amount of application screening are shown on the left hand side. There's a lot of process development, control development, scale-up, pilot plant, and so on to go through. We are working toward developing the Space Station that will support this activity. Whether materials production will occur on the Space Station or not is yet to be determined. Throughout this entire process, that scale-up issue is a critical one and Bob Naumann alluded to that in his talk.

Figure 6 expands on the scaling process between research and production. It essentially involves calibration of research, or process results versus the process environment. The process environment here is a parametric definition of the thermal, the pressure, the electromagnetic environment, and so on. Those are all process control parameters, and we are adding the new one of the weightlessness in trying to determine how to exploit it so that it augments those other process parameters.

Figure 7, entitled "Scaling Issues," shows this a little more graphically. Indicated is a hypothetical application size which is a crystal of the order of 4 quarts, or about a gallon, in some configuration. If one starts out by doing a number of process experiments (P_i) at a given volume (shown here as a volume of about 7 or 8 cc on the horizontal axis) and does this experiment as a function of g, buoyancy driven convection and scaling from dimensional analysis would indicate that there would probably be process thresholds as shown by the diagonally drawn family of curves. Point P_1 shows what would be perhaps unacceptable results. The second trial is also unacceptable. Finally, one gets low enough g at point P_5 to get diffusion growth control in this particular process. Using the the Space Station Materials Lab, one would hope to map out an environment where you knew what the process threshold was, and then you still might be faced with a projection from what you could do on a Space Station laboratory to a point design required for production. That's critical because if you do a straight-

CRITICALLY ESSENTIAL STEP

- IN SCALING FROM RESEARCH TO PRODUCTION

  CALIBRATE PROCESS RESULTS VERSUS PROCESS ENVIRONMENT

- PROCESS ENVIRONMENT IS DEFINED PARAMETRICALLY BY PROCESS PARAMETERS

  THERMAL

  PRESSURE/VACUUM

  ELECTRO MAGNETIC FIELDS

  GEOMETRY

  TIME

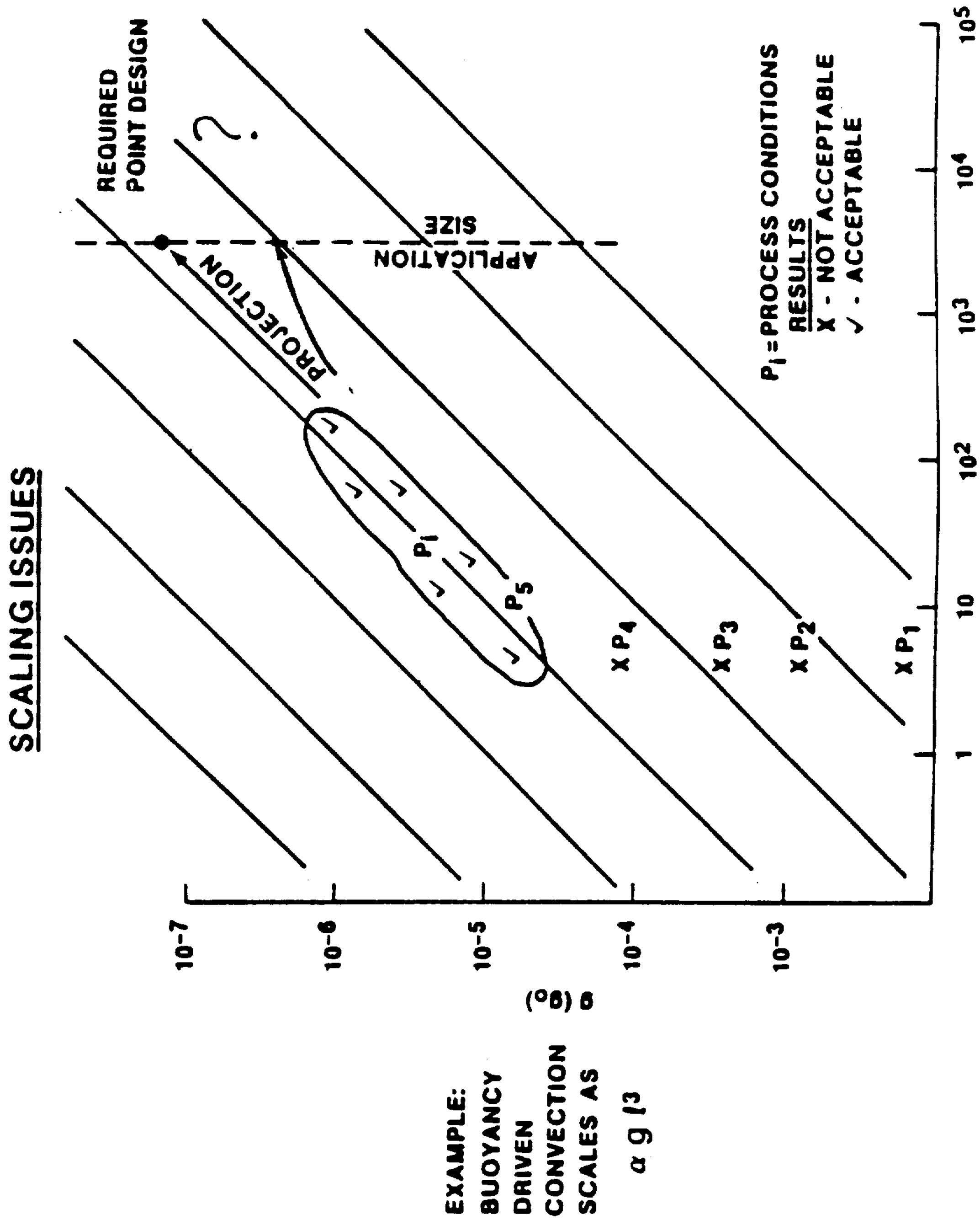
  •

  •

  •

  WEIGHTLESSNESS (THE NEW ONE)

Figure 6.



SCALING ISSUES
EXAMPLE:
BUOYANCY
DRIVEN
CONVECTION
SCALES AS
$\alpha\, g\, l^3$
g (g_o)
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
1
10
10^2
10^3
10^4
10^5
l^3 (cc)
REQUIRED
POINT DESIGN
PROJECTION
APPLICATION
SIZE
P_i
P_5
X P_4
X P_3
X P_2
X P_1
P_i = PROCESS CONDITIONS
RESULTS
X - NOT ACCEPTABLE
√ - ACCEPTABLE

Figure 7.

line projection (if that's really what it is) it drives you to much lower g levels. If there's some limiting mechanism occurring that makes the process threshold veer off horizontally, that is going to be a much less costly design to implement for production, and that becomes risk reduction to any commercial people who might be interested in this activity.

Figure 8 shows a number of process thresholds, and this does not have the scaling aspect in it, these are just different processes that we've developed with the help of Dr. Naumann and his associates. The acceleration environment in the orbit (0 to about 0.05 Hz, labeled on the horizontal axis on the bottom) includes the structural resonance regime and the vibration and noise regime. Each of those areas has its specific cause and countermeasures; and each has its specific detrimental effects on materials processing. The orbital effects, for example, drag or any frequency attributed to flying solar inertial and having the g vectors rotate, occur around 2 x 10^{-4} Hz. Things like the centrifuge operating at 22 rpm are at about 0.3 Hz. That's right in the middle of the structural resonance or close to the structural resonance of the Space Station as it's now understood. Those are issues that the materials people have to deal with when they do a detailed relation to some of the principles that Bob discussed earlier.

One item that we've come across quite a bit is that accelerometers on previous spacecraft have measured 10^{-3} g, and adequate experimental results were achieved. The data points at about 10 Hz are quite high, but because of the considerations that Bob gave earlier, they are of no consequence to these particular processes. One cannot take 10^{-3} at 10 Hz and move to the left on the chart to 0 Hz and get by with 10^{-3}. Our understanding of the fluid mechanics is getting to the point where we're quite sure that operating on that assumption would be devastating. Saying that 10^{-3} g is adequate at all frequencies since it is okay at 10 Hz is like saying that aerodynamic designs at subsonic regimes are acceptable for hypersonic flight.

EXAMPLE MICROGRAVITY REQUIREMENTS RELATED TO PROCESS

FREQUENCY VS ACCELERATION

G-LEVEL TOLERANCE FOR MONOCHROMATIC OSCILLATING DISTURBANCES POINTS AT A & B ARE SPACE LAB 3 ACCELERATION MEASUREMENTS

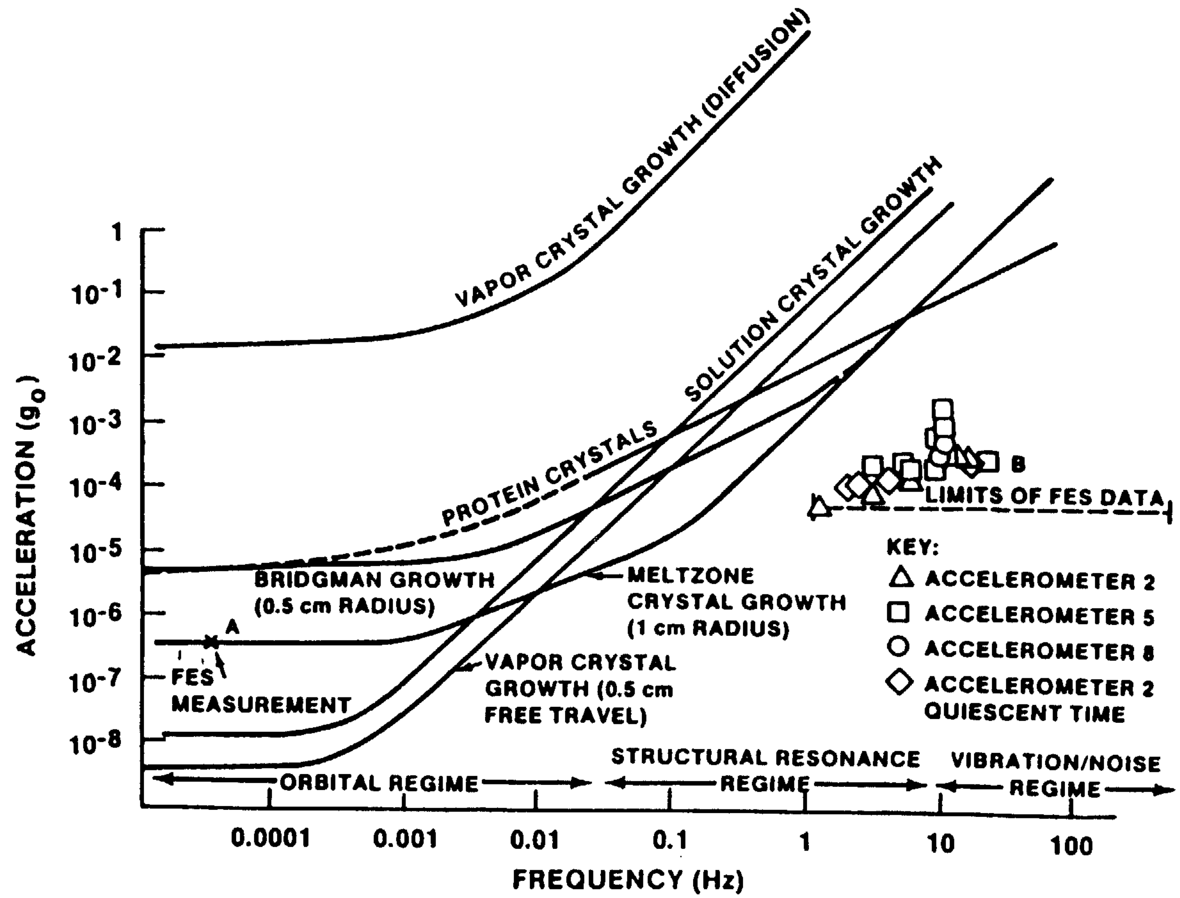


Figure 8.

Figure 9 shows another sequence of such threshold curves, g-level versus frequency, and here are indicated three options that we're studying at level B. The current Space Station requirements document officially says 10^{-5} g and that's the straight dashed line given in the figure as Option 1. As far as the wording is concerned, that acceleration level is a constant with frequency. We're looking at the option 2, which would start at 10^{-6} in the low frequency regime and then increase in the structural resonance area and the noise and vibration area to the right. These curves are a family that, for Bridgman crystal growth, correspond to the 1-, 2-, and 4-cm diameter curves for the stabilizing growth configuration with the hot part of the melt over the cold part. Another set of three curves are for the destabilizing condition, where the cold elements in the melt are over the hot elements. In that particular case, when the process is destabilized thermally, the g-level requirements go down by an order of magnitude. This would preclude a solar inertial rotation vector from being of use. Complicated schemes for rotating process payloads within the equipment that has to fit inside a universal double rack assembly that's less than a meter deep and has height and volume restrictions, power leads and other process lines are probably not feasible. I haven't seen any design that would accommodate that sort of an approach.

Tight calibration between process results and process environment will need to be done to keep the transition from research to production from being haphazard. Within that control is the calibration of the environment. There's a very detailed characterization of the g environment in all of the regimes that I mentioned, including the oscillatory area, the transient domain, and so on. What we get out of this in terms of process results will be useless in terms of projection to production if we do not know what is necessary to duplicate the process environment. So if you do have a good research result for a small sample and you don't know what environment you have to provide for a sample that's five times larger for an application market, you don't know what to do to go into production.

G-LEVEL TOLERANCE FOR MONOCHROMATIC OSCILLATING DISTURBANCES

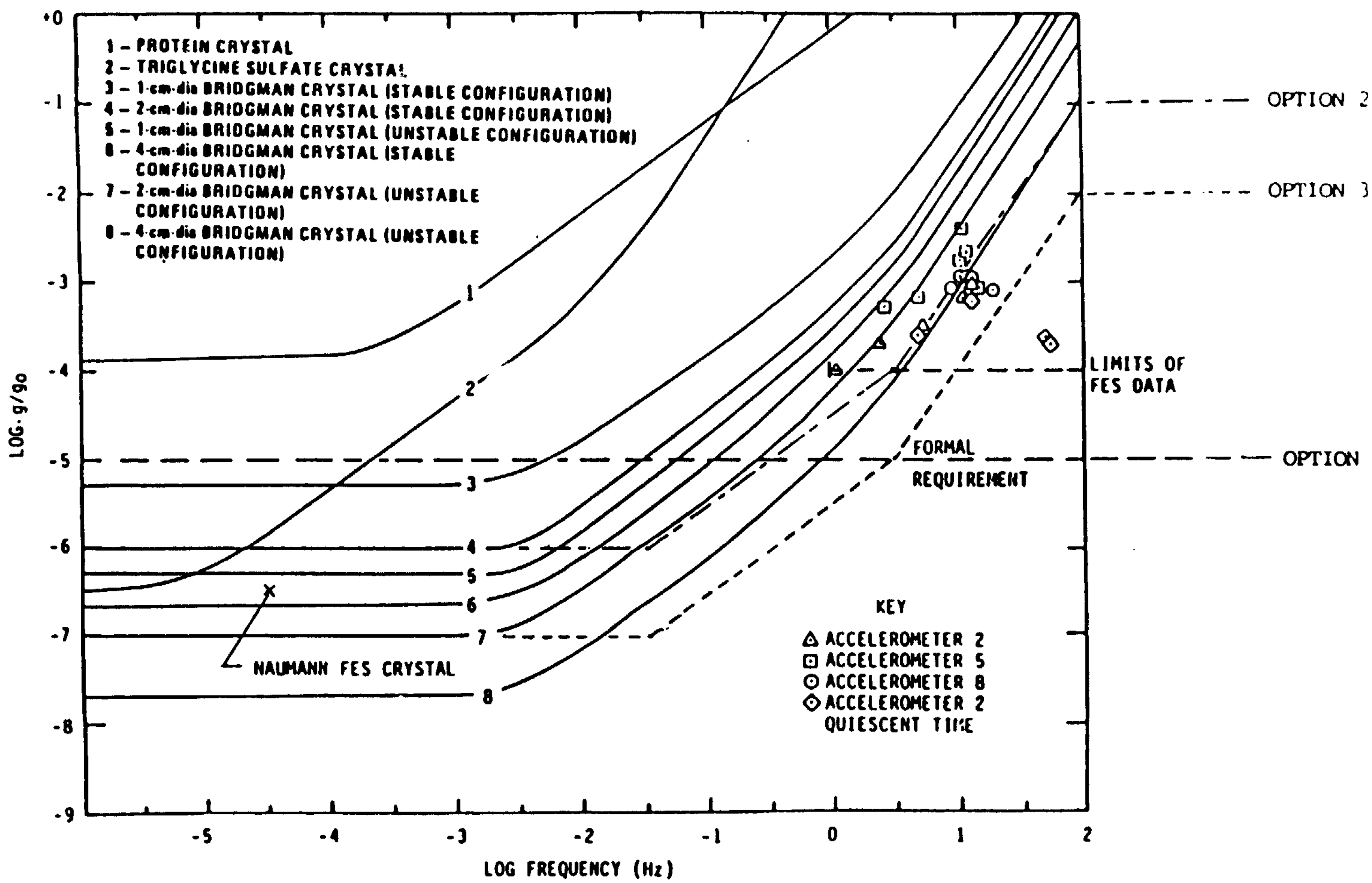


Figure 9.

I think we have learned how to deal with the thermal process parameters since the start of the bronze age. We've learned how to deal with the vacuum parameter since James Watt started using it. This new process parameter falls into that sort of a framework, but the sophistication of our methods now in fluid mechanics and so on is advanced enough so that we should be able to make great strides quickly, if we just do that tight calibration and the tight analytic modeling that are required. Figure 10 indicates a set of calibration data that we think the commercial community definitely needs. The Vander Slice Committee, which was a parallel to the current science task force on Space Station headed by Dr. Banks, made a big point that data bases are required to support commercial activity.

Characterization of the process, the environments, what you might expect to gain, are needed to map out the convective regimes that are shown in the S-1 area (Figure 10) versus the diffusive growth regimes in the S-2 area. This is a lot of detail based on dimensional analysis. We're trying to separate convective growth from diffusive control, which is the main issue. Diffusive control, as shown in Figure 11, maps detail nomograms for assessing how to scale up to a production device. This figure pertains to germanium-gallium; it has thermal gradients as one parameter. The H on the chart is the crystal diameter; R is the growth rate. Concentration gradients are shown across the horizontal axis on the bottom, and could be related to dollars in the market place at a given size. Large crystals are to the lower left-hand part of this diagram, where the g-levels keep going down. One g is shown at the top on the left-hand axis, 10^{-6} g_0 at the bottom. This is the framework that we need to provide, or to develop data for, so that we can assess the risk of going to a production effort.

Figure 12 shows the environment that needs to be characterized. It's a lot more detailed than is given here, but this shows the relative magnitudes of drag-induced accelerations, the acceleration due to attitude wobble on the Space Station, the gravity-gradient accelera-

FLUID DYNAMICS PROVIDES SCALING RELATIONS FOR SEPARATING "CONVECTIVE DIFFUSIVE" FROM "DIFFUSIVE" REGIMES

S_1 CONVECTIVE

S_2 DIFFUSIVE THROUGHOUT

S_3 & S_4 DIFFUSIVE OVER LIMITED LAYER

DIMENSIONAL ANALYSIS METHODS USED IN EARTHBOUND PROCESS CONTROL IS EXTEMDED TO LOW G USING "SCHMIDT", "GRASHOF", AND "PECLET" NUMBERS

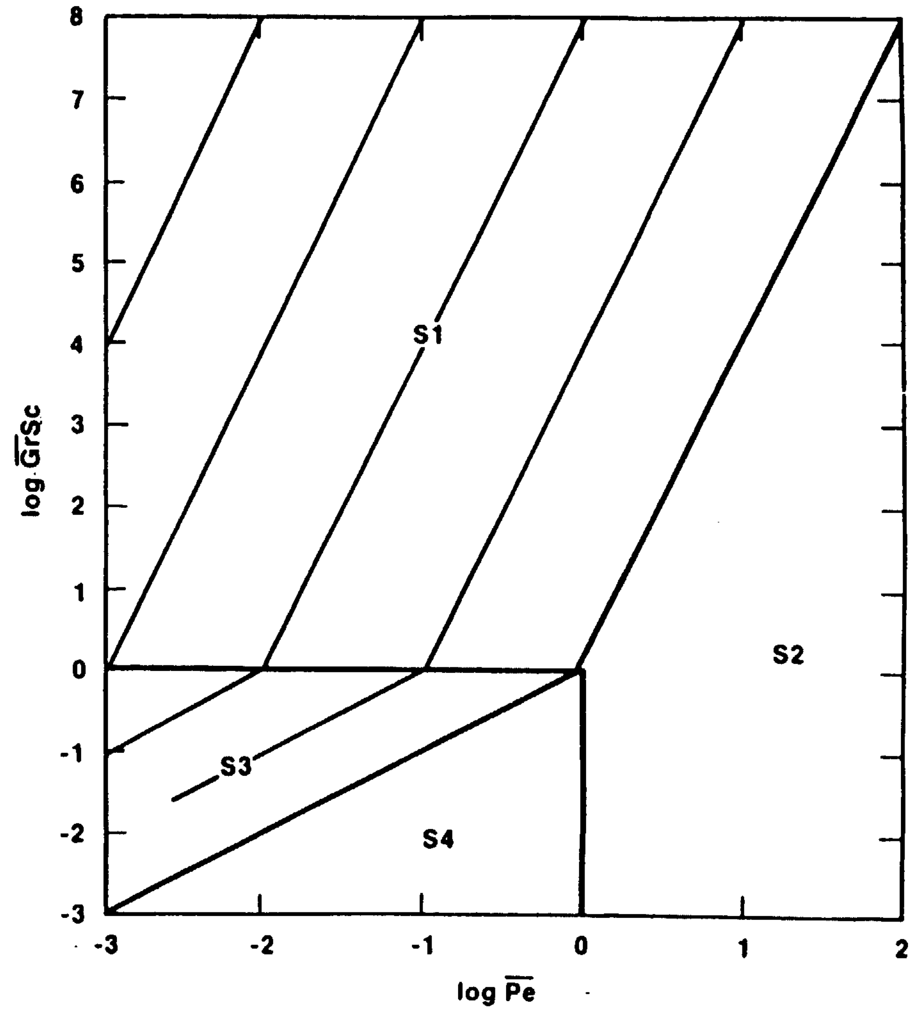


Figure 10.

G LEVEL VERSUS SIZE AND CONCENTRATION FOR THE GERMANIUM-GALLIUM SYSTEM FOR HOMOGENEOUS CRYSTALS

□ TEXUS

★ ASTP

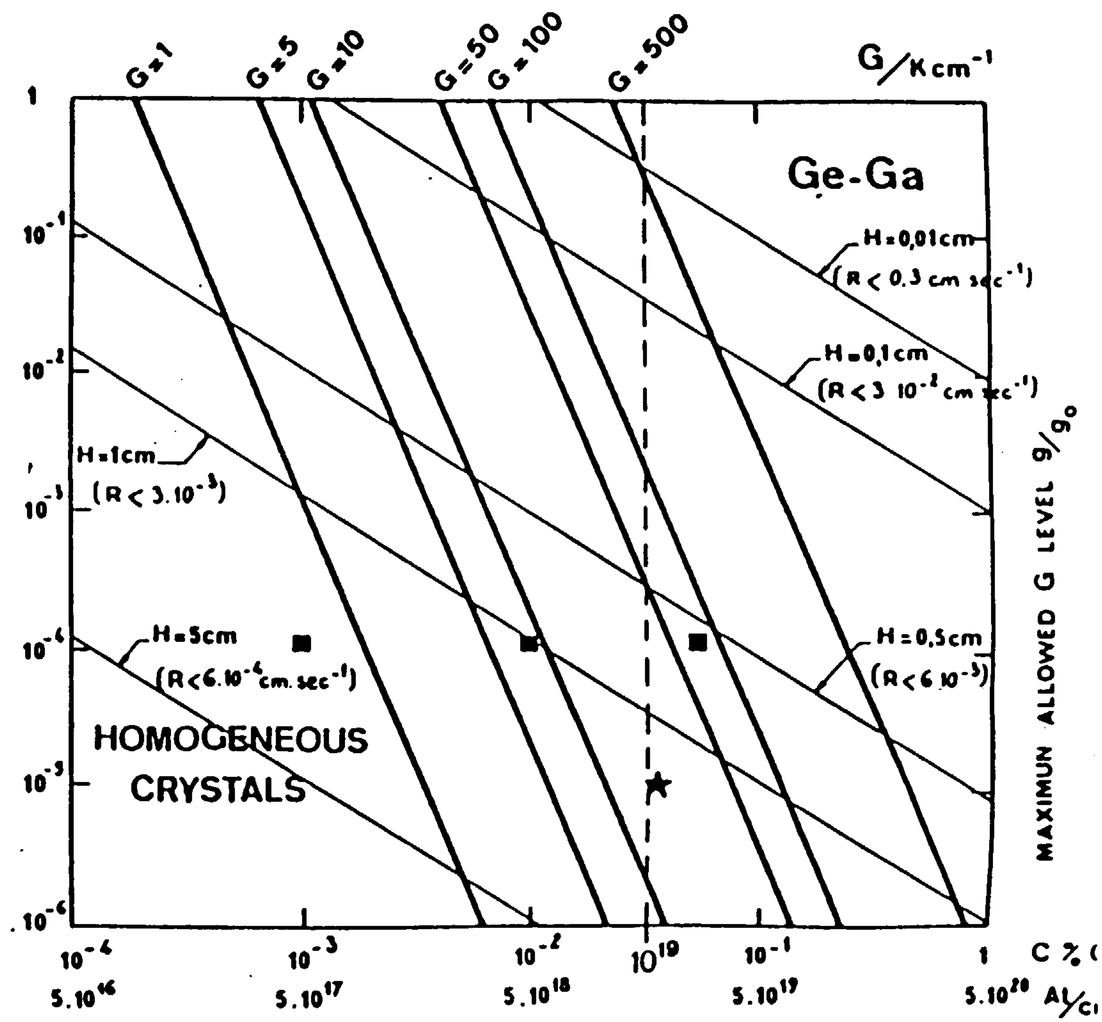


Figure 11.

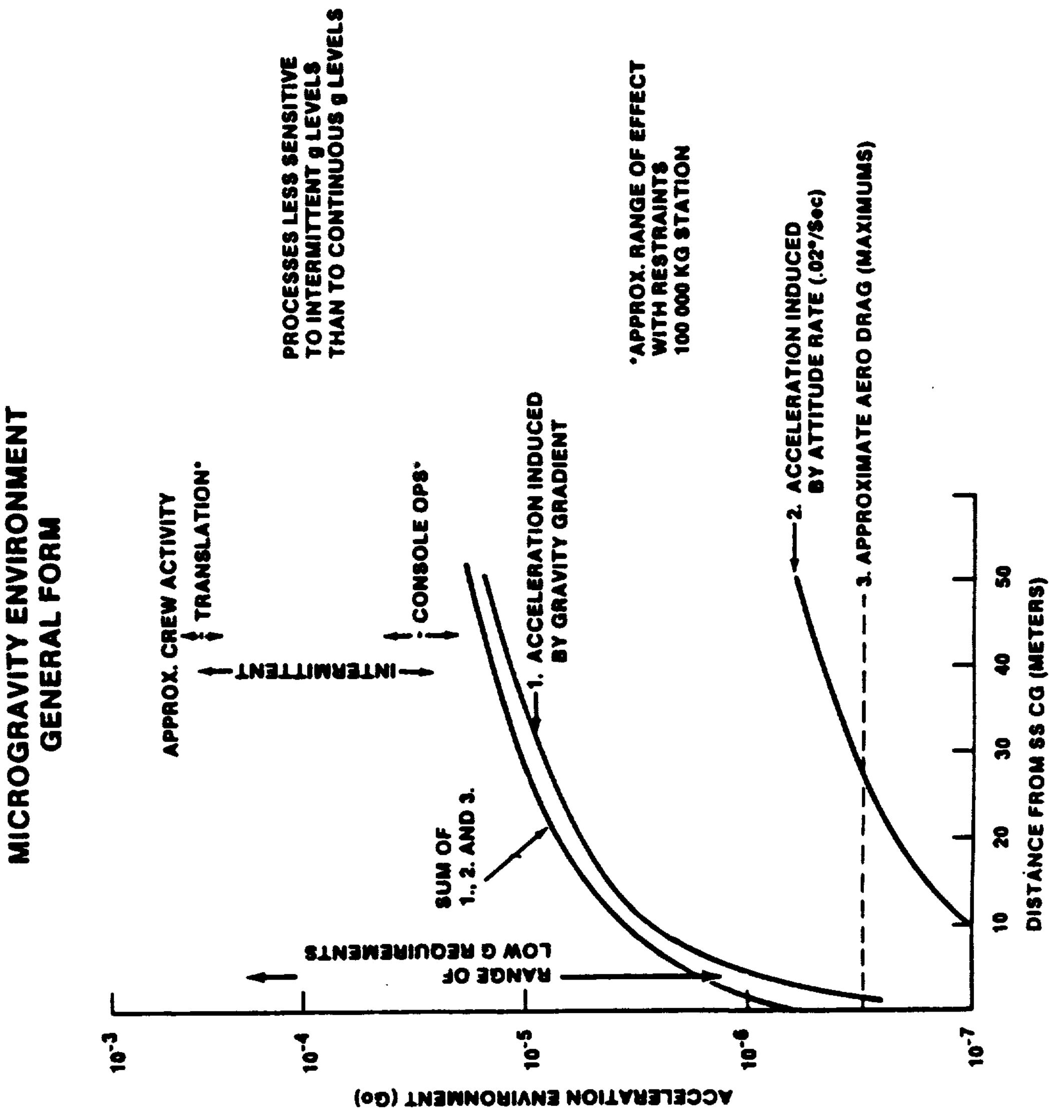

MICROGRAVITY ENVIRONMENT
GENERAL FORM
APPROX. CREW ACTIVITY
TRANSLATION*
INTERMITTENT
CONSOLE OPS*
PROCESSES LESS SENSITIVE
TO INTERMITTENT g LEVELS
THAN TO CONTINUOUS g LEVELS
RANGE OF
LOW G REQUIREMENTS
SUM OF
1., 2. AND 3.
1. ACCELERATION INDUCED
BY GRAVITY GRADIENT
*APPROX. RANGE OF EFFECT
WITH RESTRAINTS
100 000 KG STATION
2. ACCELERATION INDUCED
BY ATTITUDE RATE (.02°/Sec)
3. APPROXIMATE AERO DRAG (MAXIMUMS)
ACCELERATION ENVIRONMENT (Go)
10-3
10-4
10-5
10-6
10-7
10
20
30
40
50
DISTANCE FROM SS CG (METERS)

Figure 12.

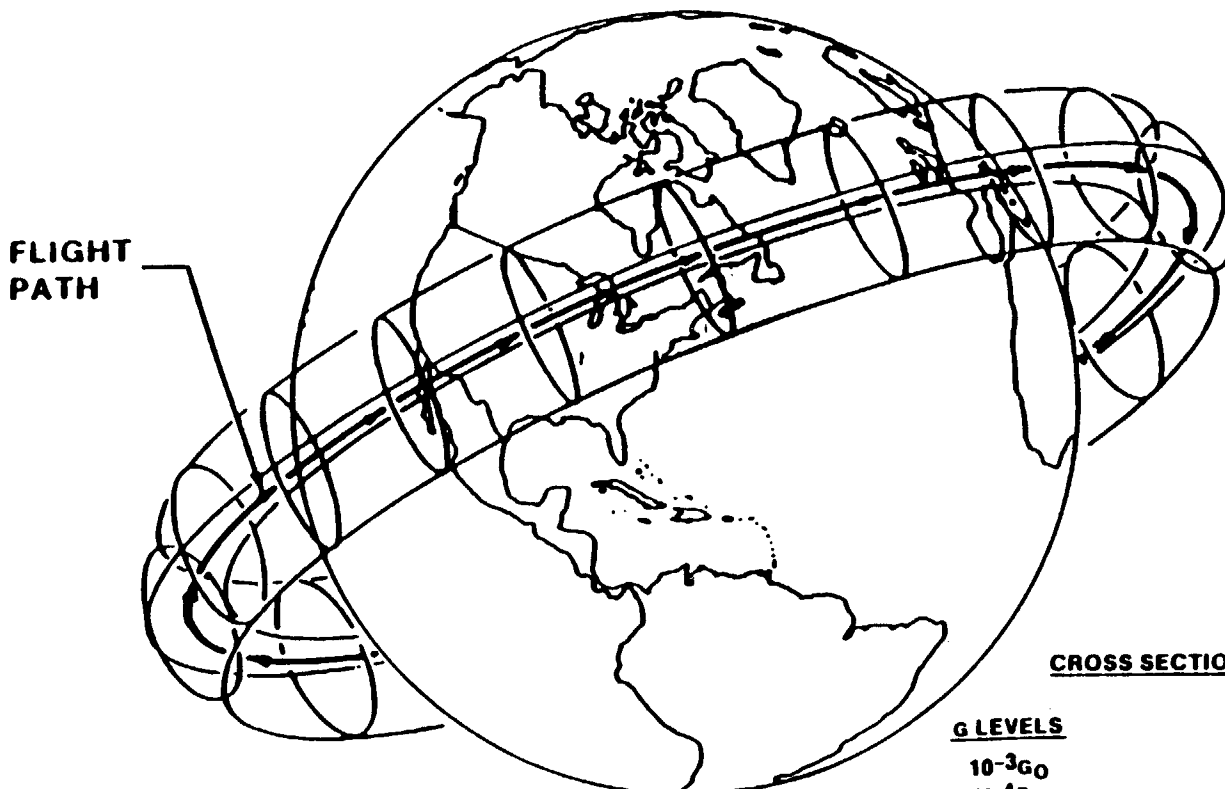
CHARACTERIZATION OF MICROGRAVITY ENVIRONMENT

- 3- DIMENSIONAL VECTOR FIELD
  - VS FREQUENCY
  - VS TIME
  - LINEAR COMPONENTS
  - ROTATIONAL COMPONENTS
- NEEDED SENSITIVITY LEVELS MIGHT COME FROM COMPUTATIONAL FLUID DYNAMICS
- DATA FORM SHOULD FIT EXPERIMENT DESIGN

Figure 13.

tions, the range of the intermittent activity on the Station and so on. All of the frequency scale is on one chart, so one should not read in here that the intermittent activity has the same effect as the g at the same level for, say, gravity gradient. One has to go back to the frequency curves on Figures 8 and 9 to get that component of the data. Figure 13 indicates the type of characterization that we need to do to the g field, and the instrumentation to do it with, with emphasis on 10^{-3} to 10^{-4} Hertz.

Figure 14 is a picture of the acceleration level that one can acheive in the current Space Station configuration in the local vertical-local horizontal mode. In the lower right-hand corner are the sizes of that elliptic torus around the Earth. At 10^{-6} g, that's 16 m by 5.3 m. At a nano-g that's 16 mm by 5.3 mm, so anybody that needs a nano-g has problems if he has something as large as a marble to work with. Figure 15 indicates the issue more clearly. Here again is that scaling chart from Figure 7, and in the upper right-hand area, there are some intersect lines on process thresholds. That's the approximate cap on what you can do in low-earth orbit because the sample starts getting bigger than the environment that's available. What this implies is that, as you go into assessing production, you may well run into that cap. For example, there is an asterisk along the horizontal axis on the left that is an approximate location of a curve for a Bridgman crystal growth of germanium-gallium. Obviously, that curve would intersect the application size above the limit where, from an acceleration standpoint, you could do it. That's a regime above which the magnetic methods that Dr. Naumann mentioned would be in order. The other mechanism would be to go to a much higher orbit. If you went to about a 4,000 n.mi. orbit, you'd be two Earth radii out from the center of the Earth and that cap would move off and cross through the "C" in Commercial. Going to a much higher orbit and incurring a much different, harsher environment does buy you something, but it's extremely expensive. The main point I'd like to leave with you here is that this gives a strategic framework from which to decide where to put the thrust for later



CROSS SECTION OF ISO G ENVELOPES

G LEVELS	MAJOR AXIS CROSS PLANE	MINOR AXIS RADIALLY
$10^{-3}G_O$	16000 M	5300 M
$10^{-4}G_O$	1600 M	530 M
$10^{-5}G_O$	160 M	53 M
$10^{-6}G_O$	16 M	5.3 M
$10^{-7}G_O$	1.6 M	.53 M
$10^{-8}G_O$	16 CM	5.3 CM
$10^{-9}G_O$	16 MM	5.3 MM

Figure 14.

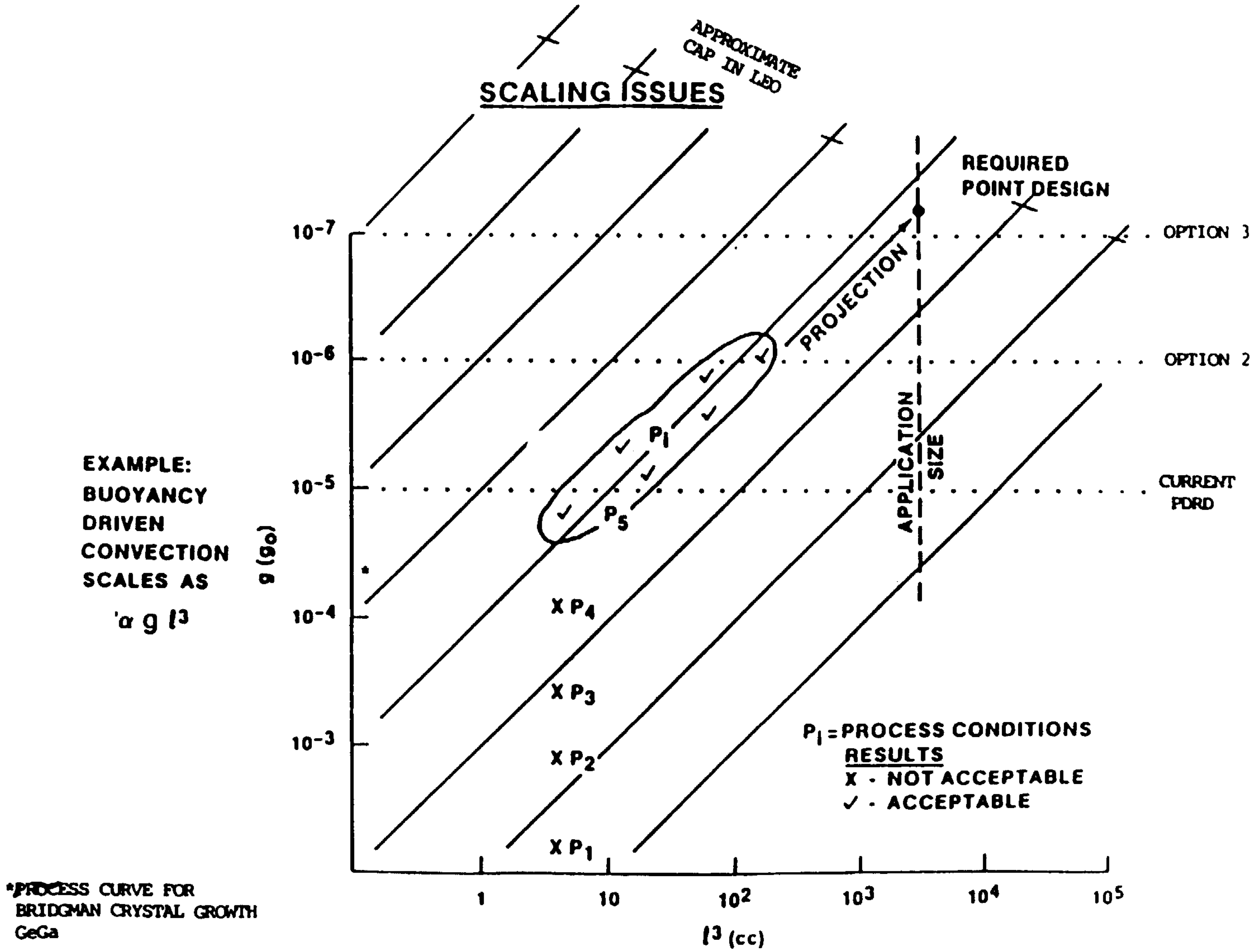

SCALING ISSUES
APPROXIMATE CAP IN LEO
REQUIRED POINT DESIGN
OPTION 3
OPTION 2
CURRENT PDRD
PROJECTION
APPLICATION SIZE
EXAMPLE:
BUOYANCY
DRIVEN
CONVECTION
SCALES AS
'α g l^3
g (g_o)
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
P_1
P_5
X P_4
X P_3
X P_2
X P_1
P_i = PROCESS CONDITIONS
RESULTS
X - NOT ACCEPTABLE
✓ - ACCEPTABLE
1
10
10^2
10^3
10^4
10^5
l^3 (cc)
*PROCESS CURVE FOR BRIDGMAN CRYSTAL GROWTH GeGa

Figure 15.

production. We need to be careful with our commercial constituency in materials processing and point out that there are certain things that we might not be able to bring to fruition in low-Earth orbit. It might take a higher orbit and a much more capable transportation system. It might be something that is available 100 years from now instead of 10 years from now.

Figure 16 is a view that you've seen previously but our basic configuration in which 10^{-5} g_0 is easy to get. That is indicated on Figure 17. The large ellipse is the profile of 10^{-5} g_0 at the dc level, not the oscillatory, the bump, the grind, the rattle and roll activity on the Station, but just the gravity gradient component. The small ellipse is the 10^{-6} contour. I don't think we can change the c.g. of this configuration to get the laboratory modules out of the 10^5 envelope. I think we need to consider a micro-g or 2 micro-g for the static g-level. This would require c.g. maintenance and control as we add payloads to the upper and lower booms, and may be a critical technology for the countries involved in the Space Station activity.

Figure 18 is a recap showing the LVLH configuration and its g environment shown on the left, and the solar inertial configuration on the right. The solar inertial has a high degree of vector direction change. Stable processing configurations would go to unstable processing configurations, whereas the environment on the left lets you stack modules longitudinally along the flight path. You can't do that on the right with the solar inertial. The small total volume that you can exploit in the solar inertial, unless your process happens to be ideally suited for reversal of the field, is just too great a penalty to pay.

Figure 19 shows another way of looking at the structure of the field that we need to start considering. As you move around in the fluid element in your process, up is not always the same direction. It moves around. If your process element represented that sphere, the forces on the surface of that sphere are shown with respect to the radial direction, which is up and the cross-plane direction, which is

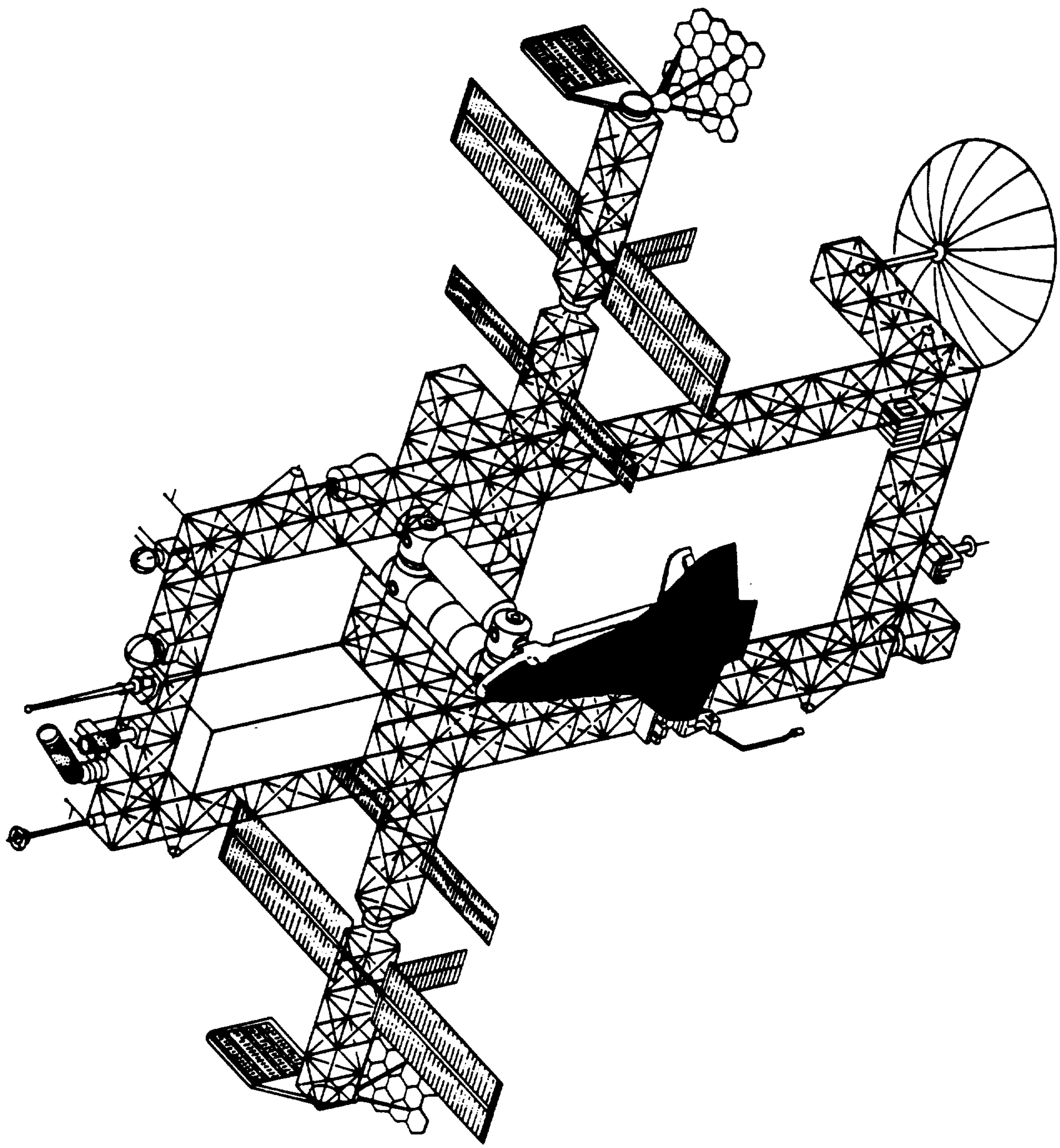


Figure 16.

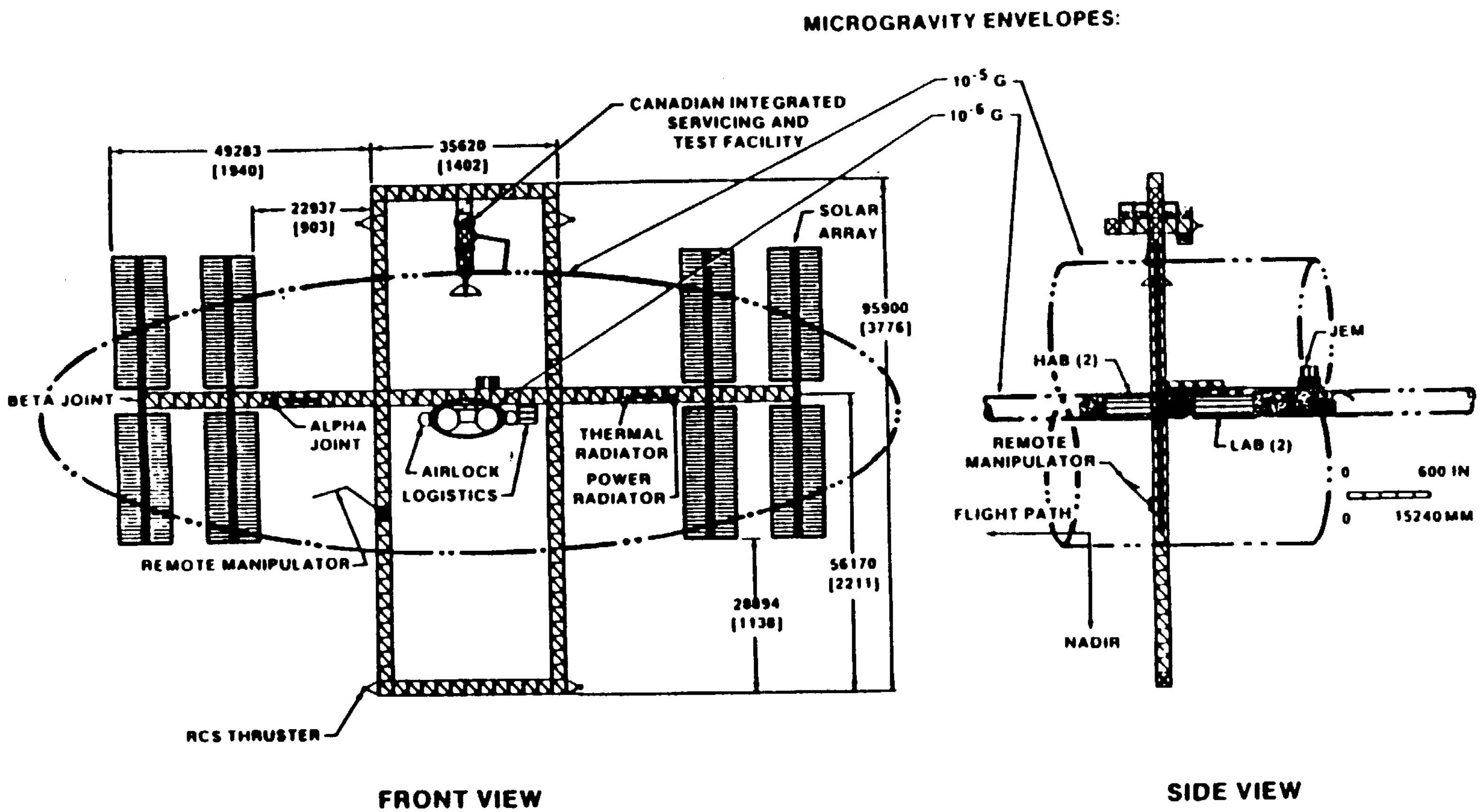

MICROGRAVITY ENVELOPES:
10^{-5} G
10^{-6} G
CANADIAN INTEGRATED SERVICING AND TEST FACILITY
49283 [1940]
35620 [1402]
22937 [903]
SOLAR ARRAY
95900 [3776]
BETA JOINT
ALPHA JOINT
AIRLOCK
LOGISTICS
THERMAL RADIATOR
POWER RADIATOR
REMOTE MANIPULATOR
56170 [2211]
28894 [1138]
RCS THRUSTER
FRONT VIEW
JEM
HAB (2)
LAB (2)
REMOTE MANIPULATOR
FLIGHT PATH
NADIR
0 600 IN
0 15240MM
SIDE VIEW

Figure 17.

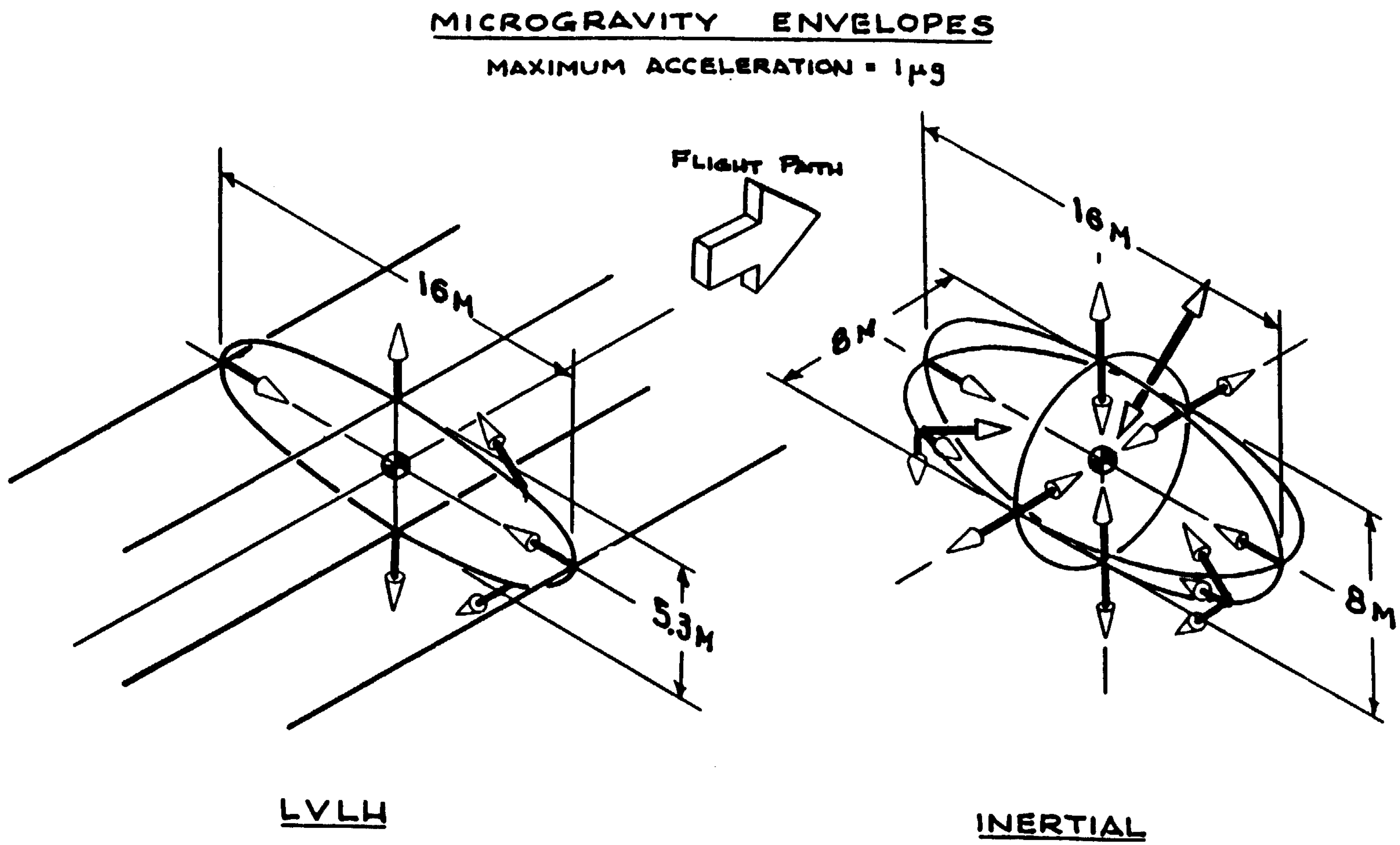

MICROGRAVITY ENVELOPES
MAXIMUM ACCELERATION = 1μg
FLIGHT PATH
16M
5.3M
16M
8M
8M
LVLH
INERTIAL

Figure 18.

STRUCTURE OF GRAVITY GRADIENT FIELD

FOR A CIRCULAR ORBIT, THE ACCELERATION DUE TO GRAVITY GRADIENT EFFECTS ON A POINT R METERS FROM THE FLIGHT PATH OF THE CG CENTER OF GRAVITY IS:

DISTANCE FROM CG (M)	ACCELERATION ($10^{-6}G_0$)	
	RADIAL	CROSS PLANE
R	A_R	A_{CP}
1	0.375	0.125
2	0.75	0.25
4	1.50	0.50
8	3.00	1.00
16	6.00	2.00
32	12.00	4.00
64	24.00	8.00

- ORBIT ALTITUDE: 270nm, 500km
- Z AXIS RADIAL FROM EARTH
- Y AXIS CROSS PLANE
- X AXIS VELOCITY VECTOR (⊥ TO CHART)

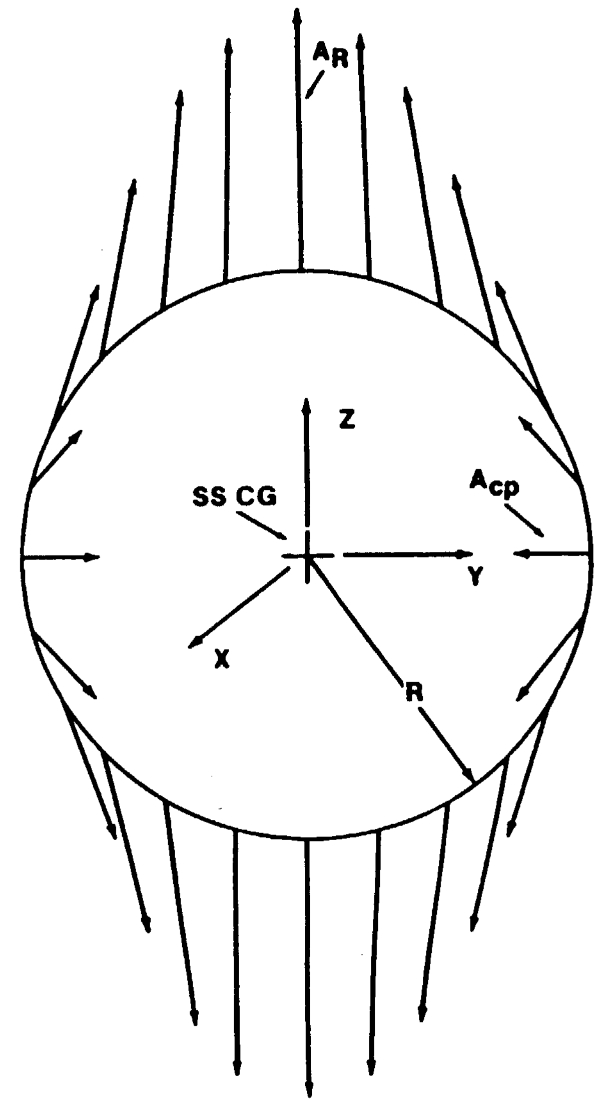


Figure 19.

horizontal on this chart. Figure 20 shows what's happening inside this spherical fluid element. The fields are changing throughout, and our fluid dynamics modeling shows the field to be generally constant and in a constant direction. These are time stationary fields, but they do change with position. There could very easily be some damping characteristics that one might be able to utilize in this regard, but what they are is a question for the expert in computational fluid dynamics.

Figure 21 indicates some of the drag aspects that we're faced with. Currently the program is taking the approach that it's going to design a station so that it could operate at an altitude that would incur an average drag of 0.3 micro-g. But within the orbit, we won't be flying a constant fixed drag acceleration because that requires moving up and down. The Space Station altitude has not yet been specifically picked, only the design range of the station has been set. Somebody will want to fly the Station to its extreme altitudes so it could still be a threat, so the altitude flight issue must still be addressed.

Figure 22 is a list of things to watch on the station from a user and an implementer's viewpoint in the materials processing area. TEA is torque equilibrium attitude. The station doesn't fly exactly with the boom structure vertical to the Earth's surface; there can be two or three degrees of wobble, depending on momentum conservation considerations in the attitude control system. There will be significant changes when the Shuttle docks. Generally it will be noisy enough and we'll be doing enough things in the laboratory where we would probably shut down operations while the Shuttle is docked. We don't envision the Shuttle to be there for long. The TEA limit of a few degrees is the most likely limit. As you get out farther and farther on the cantilever, flying along the flight path of the center of gravity, any torque equilibrium attitude can tip you up right out of your required g environment. The center of gravity will migrate with growth, as some of the payloads are several tens of thousands of pounds, and are going to get mounted to the upper or lower booms. The center of gravity would move tens of feet. There is a possibility for manifesting the payloads

GRAVITY GRADIENT STRUCTURE FOR EXTENDED VOLUMES

THE COMPOSITE STRUCTURE OF THE GRADIENT FIELD OVER EXTENDED VOLUMES IS INDICATED HERE. R_0, R_1, & R_2 ARE THE RADII OF THE OUTER, MIDDLE & INNER CIRCLES

DISTANCE FROM CG (M)	ACCELERATION ($10^{-6}G_0$)	
	RADIAL	CROSS PLANE
R	A_R	A_{CP}
1	0.375	0.125
2	0.75	0.25
4	1.50	0.50
8	3.00	1.00
16	6.00	2.00
32	12.00	4.00
64	24.00	8.00

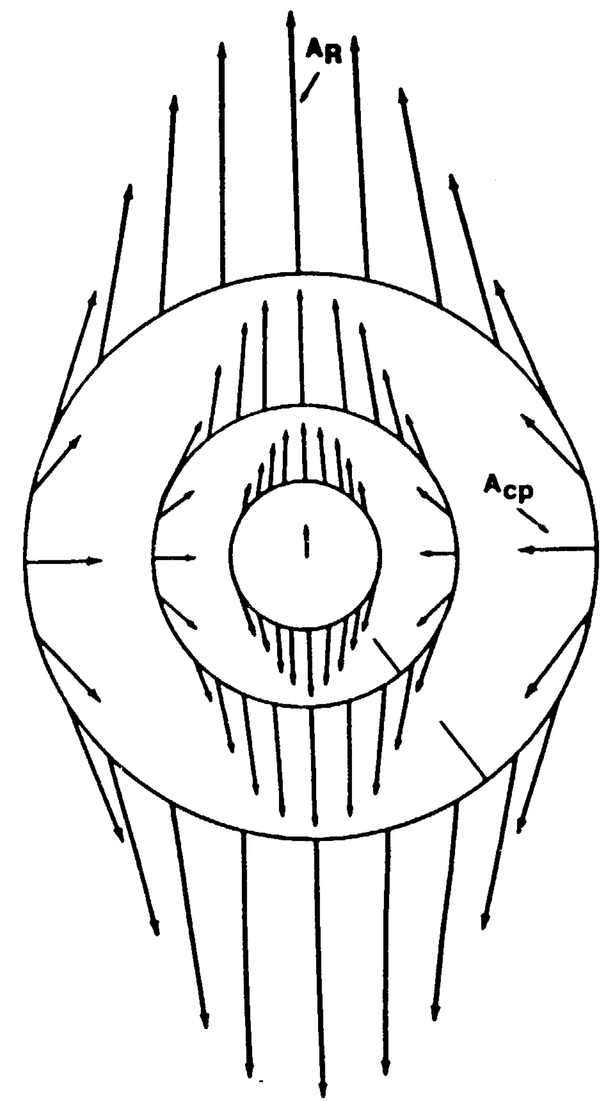


Figure 20.

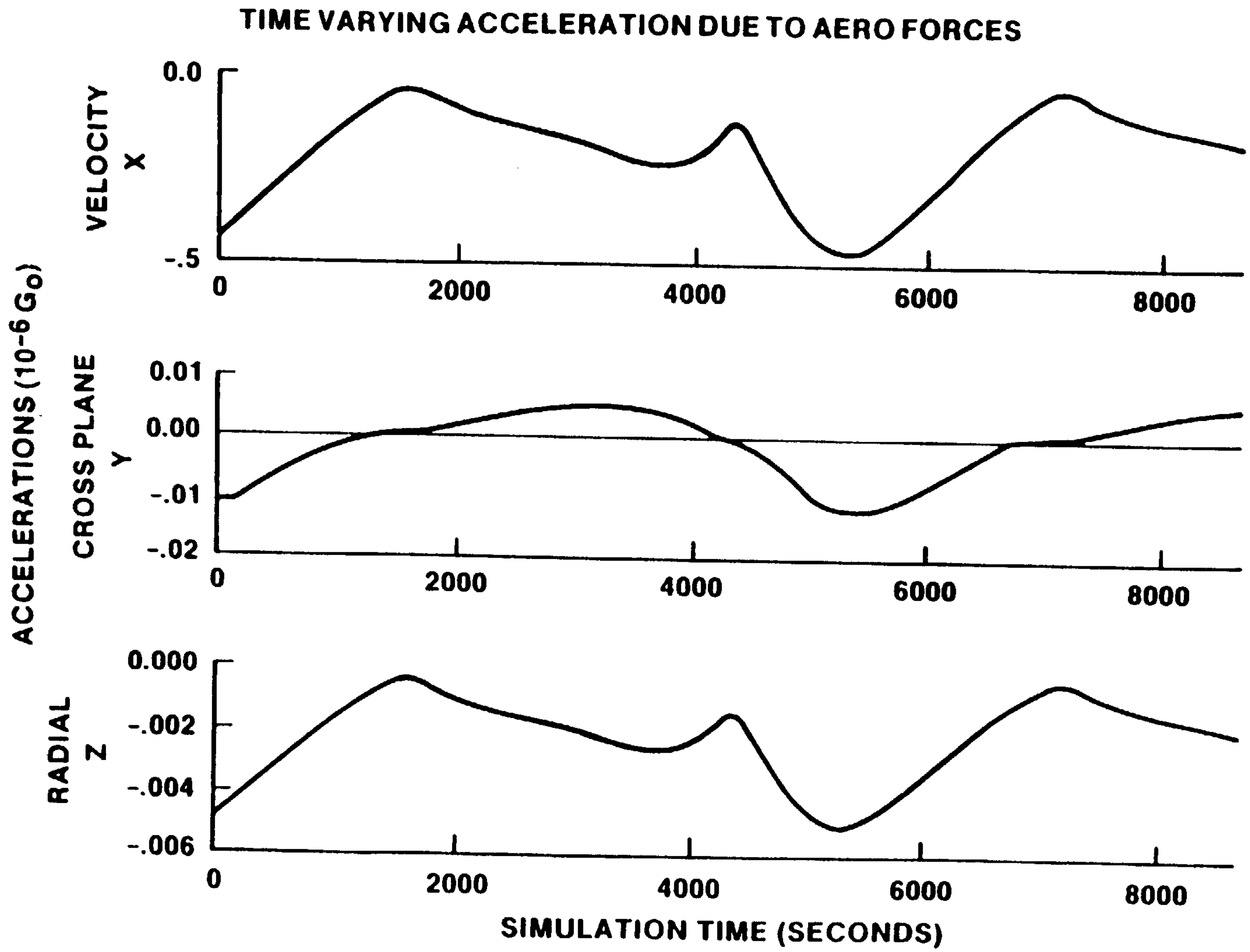

TIME VARYING ACCELERATION DUE TO AERO FORCES
ACCELERATIONS (10^{-6} G_o)
VELOCITY
X
0.0
-.5
CROSS PLANE
Y
0.01
0.00
-.01
-.02
RADIAL
Z
0.000
-.002
-.004
-.006
0
2000
4000
6000
8000
SIMULATION TIME (SECONDS)

Figure 21.

SPACE STATION THINGS TO WATCH

- TEA - FLIGHT ATTITUDE/MODE
- CG MIGRATION W GROWTH
- CG FLUTTER W OPS
- DRAG PROFILE
- STRUCTURAL RESONANCE
- VIBRATION & NOISE
  - ROTARY & RECIPROCAL EQUIPMENT
  - CREW - ANIMALS
- LOCATION OF

Figure 22.

THE KEY TO THE GORDIAN KNOT
OF EXPLOITING MICROGRAVITY
AND SCALE UP

FLUID DYNAMICS
AND
COMPUTATIONAL FLUID DYNAMICS
WITH
EXPERIMENTAL RESEARCH & DEVELOPMENT

Figure 23.

in such a way that that doesn't happen. There's still room for using ballast units of waste solid or liquid materials on the station to do this. This really hasn't been addressed yet, but people like you will have to bring the message for the need to stay at a micro-g or two micro-g.

Question: Is there is any effort in fluid dynamics?

Demel: The answer is yes. Code E, that's Dick Halpern's organization in NASA Headquarters, has a considerable effort in computational fluid dynamics. It's getting bigger. At level B in the Space Station, we're funding, or will be funding, some activity in that regard to tailor the answers of the work that we need to characterize the environment for the Space Station, what the implications are on Space Station design. Aerodynamics on the Shuttle were done by computational fluid dynamics and it was supported by wind tunnel testing. But a lot of the data base that is used in Shuttle operations comes from the computational part. I think that's a very valid model for us to use here in materials processing.

Alex Lehoczky, NASA/MSFC: Couldn't forces in the melt due to solute concentration gradients be a major factor as well?

Demel: Alex was making the point that all of this is based upon convection considerations and not solution considerations or concentration considerations, that's true. Getting the thermal aspects under control I think is essential to providing the access to the problems so you can address the solutal aspects.

Lehoczky: What I'm referring to is the driving force.

Demel: Yes.

Ulf Merbold, ESA/ESTEC: Have you looked at thrusters to exactly counteract the drag forces?

Demel: Yes. Bob made mention of the DISCOS experiment or the TRIAD experiment that was flown in the early 70's, I think around '74 or so. That was a drag-free satellite oriented toward assessing true gravity orbits nonaffected by drag, photon pressure, electric fields, or whatever. But in that experiment they demonstrated a sensing and control capability to maintain down to 10^{-11} or 10^{-12} g in the very core of a test mass, not for a very large volume. It still has dimensions of a few microns at those levels. But the control technology has been with us, for a satellite, since the early 70's. Now applying that control technology to the station is another issue. We have been discussing the resistojets for drag make-up but in terms of having engines that would have a variable thrust to exactly counter drag as it varies in the orbit, we haven't really addressed that. The people who are concerned with reboost are concerned about the reliability of the engines and making sure the Space Station doesn't get into an attitude or altitude where it deorbits and that sort of thing. We have been reviewing that constant drag makeup to do a detailed counteraction of drag in the orbit as a growth capability on the station and really not made a big point of it at this point. That's something we can fix later; we're concentrating on those things that have to be fixed now in the basic configuration, but yes that is a way to take care of that drag component.

Fred Henderson, Teledyne Brown Engineering: That drag level -- there may be something about the geometry I didn't understand, but it would seem that atmospheric drag you could move the center from the very center of the geometry rather than fly a reaction type acceleration.

Demel: No, when you do your vector summation of all the effects, and take in account the attitude wobble on the spacecraft, the volume at a given g level is shifted in the velocity direction as you mentioned. But you're continually driving or going to a lower altitude. You're spiraling in continuously at tens to a 100 meters per orbit. When you insist that a process chamber spiral in with you, it's experiencing the same drag forces constantly that the station does.