Section 7

Predicting Residual Acceleration Effects on Space Experiments

Emily Nelson
Computational Microgravity Laboratory
M/S 105-1, NASA Glenn Research Center
Cleveland, OH 44135
Emily.S.Nelson@grc.nasa.gov

Symbols, acronyms and abbreviations

Acronyms

CCU	Cell Culture Unit
CFD	computational fluid dynamics
CSC	cell specimen chamber

Roman characters

a	acceleration
$B=\rho gV$	buoyancy
C	concentration
c_p	heat capacity
D	drag
D_C	diffusivity of species
D_m	mass diffusivity
F	force
g	gravity
k	thermal conductivity
m	mass
p	pressure
Pr	Prandtl number$=\nu/\alpha$
S	source term
Sc	Schmidt number$=\nu/D$
u	velocity
V	volume
$W=mg$	weight

Greek characters

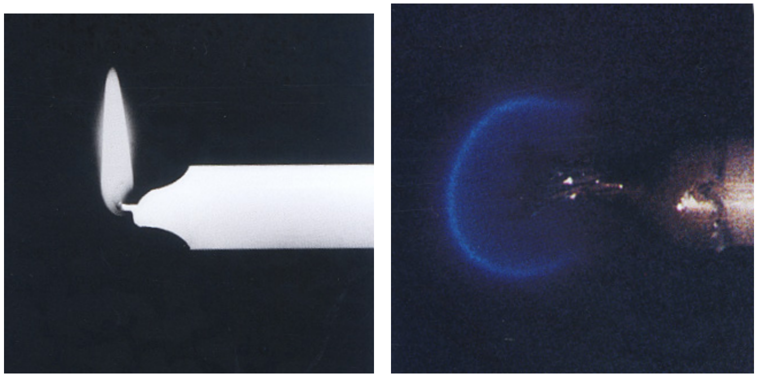
$\alpha=k/\rho c_p$	thermal diffusivity
μ	absolute viscosity
ν	viscosity (momentum diffusivity)
ρ	density
σ	surface tension
τ	shear stress. For Newtonian fluid, 2D, cartesian:

$$\tau = \mu\left(\frac{\partial\tilde{u}}{\partial x} + \frac{\partial\tilde{v}}{\partial y}\right)$$

Subscripts/Superscripts

b	bubble
d	droplet
i	spatial index
l	species index
m	fluid medium
n	temporal index
osc	oscillatory
p	particle
qs	quasisteady
t	transient

How does acceleration affect experiments?



1g µg

- ***Affects weight*** (loading)
- ***Modifies fluids transport*** processes
    - natural convection
    - sedimentation, settling
    - mixing, separation
    - allows other phenomena to be unmasked through decreased convection
- ***Changes stability thresholds***, e.g., interface between immiscible fluids, onset of convective instability, triggering of signal transduction pathways

> Gravity is one type of acceleration; other accelerations can affect mass in gravity-like ways

How can we predict residual acceleration effects?

Using an appropriate model of the acceleration, analysis tools include:

- ***theoretical*** analysis
  - order-of-magnitude analysis
  - exact solution of a simplified problem
  - asymptotic analysis
- ***numerical*** simulation
  - traditional finite difference/finite volume/finite element approach
  - stochastic approach
- ***experimental*** testing (ground-based)
  - ground-based facilities, e.g., KC-135, drop tower
  - vibrating platforms, centrifuge, clinostat (be sure to identify/quantify local acceleration field)
- ***examine previous experiments***/literature survey
- ***insight*** (and maybe a little luck)

How can we model acceleration for analysis?

- Estimate appropriate ***time scale(s)*** for experiment

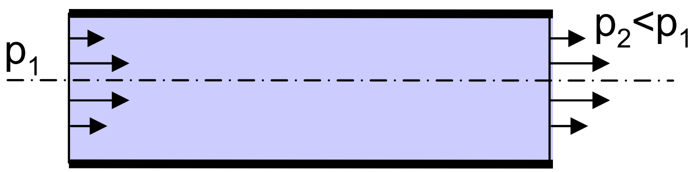
- ***Separate out the various components*** of residual acceleration from spectral analysis or from predictions:
  - Analysis can be performed in the temporal or spectral domain
  - Examine accelerations ***individually***
    - ***quasisteady*** (<0.01 Hz): magnitude, orientation, frequency(?), duration (i.e., period > 100 sec?)
    - ***oscillatory***: frequency content, amplitudes, orientation, cutoffs, stationarity
    - ***transient***: magnitude, duration, orientation, time delay between transients
  - Examine accelerations ***together***

Transformation to temporal domain ⇨

$$g_i(t) = g_{qs,_i} + \sum_n g_{o,_i} \sin(2\pi f_n t) + g_{t,_i}(t)$$

What can drive motion?

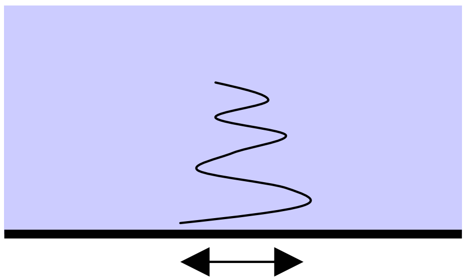
Pressure gradients



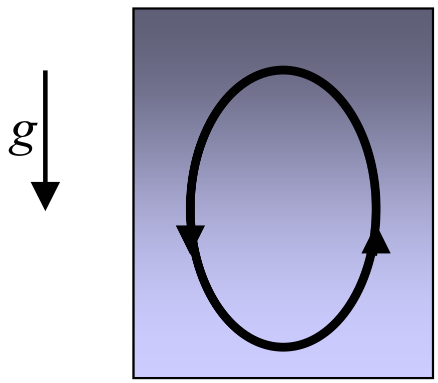
And a whole host of other forces…

- mechanical stirring
- surface tension
- electromagnetic fields
- electrokinetic forces
- chemical reaction
- ...

Boundaries

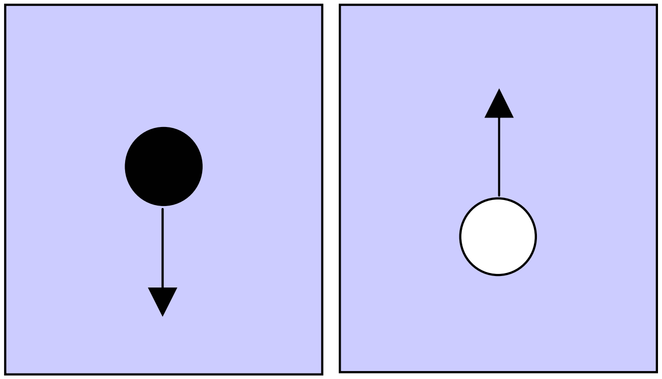


Density gradients in continuous fluids

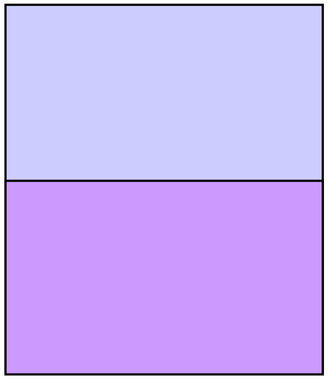


Density gradients at interfaces

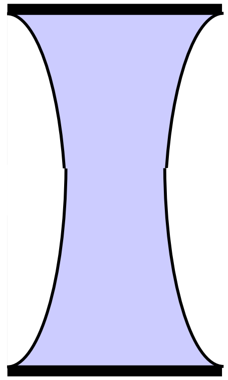
Particles, drops and bubbles



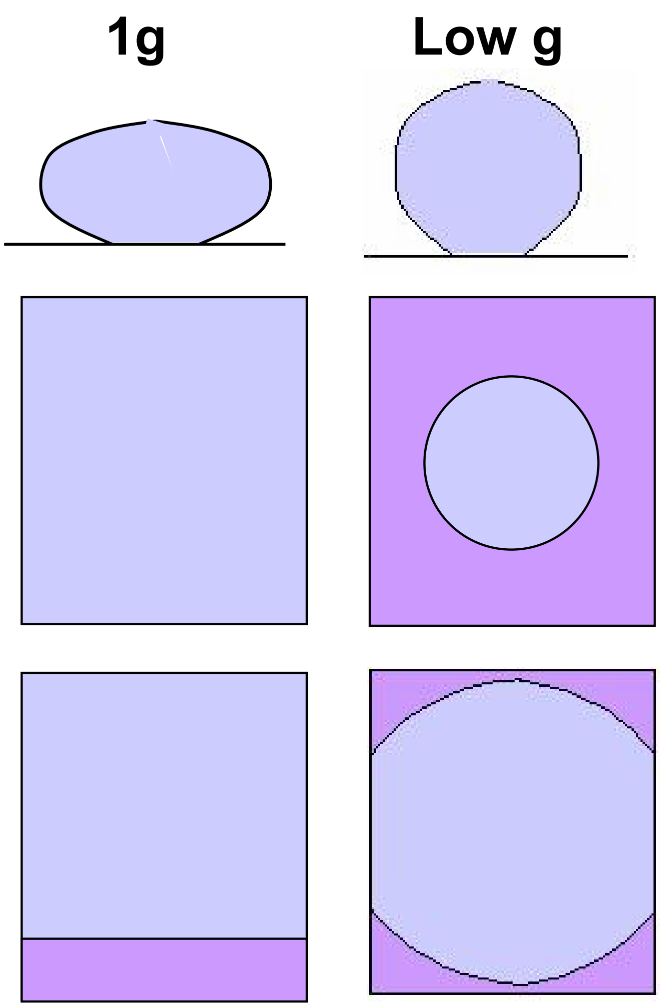
Immiscible fluids



Liquid bridges



Immiscible interfaces



Even large droplets can be spherical in microgravity

In low g, the fluid that preferentially wets the walls will encapsulate the other fluid (to the best of its ability)

The shape of the interface at low g is a function of wetting properties, relative volumes of the fluids, chamber geometry, and **g**

Effect of quasisteady g, g_{qs}

- "Quasisteady" is (somewhat arbitrarily) defined as ***f* ≤ 0.01 Hz**

- Primary contributions to quasisteady accelerations are due to ***atmospheric drag*** (primary variation over an orbital period of 90 minutes) in the direction opposing vehicle motion and ***gravity-gradient forces*** (~ const if center of mass and experiment location remain the same)

- Researchers must consider ***experiment sensitivity*** to:

  - ***magnitude*** of g (upper and lower thresholds) (expect a few μg on the Shuttle and on the International Space Station)

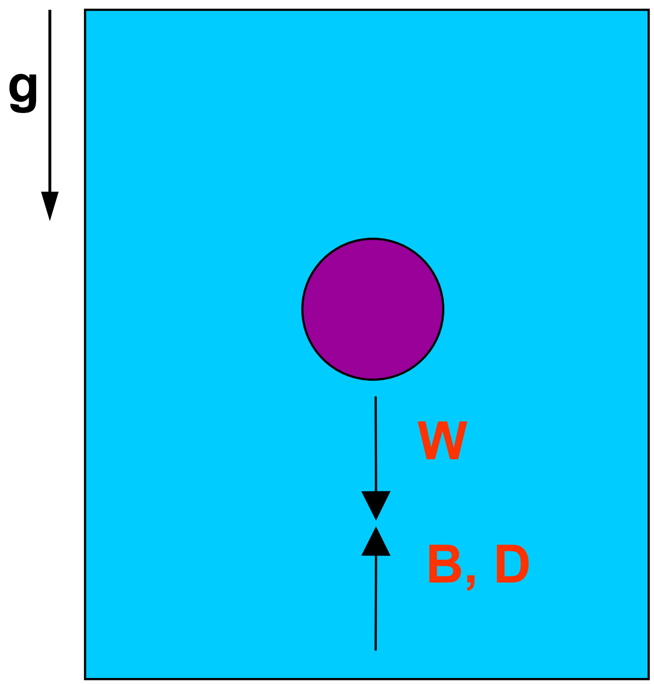
  - ***orientation*** of g (expect at least several degrees of variation in orientation over an orbital period)

  - in some cases, an experiment's quasisteady regime may not coincide with this definition and temporal variations must be considered

- Is there a ***floor*** or ***ceiling*** for g response in terms of magnitude, orientation and/or frequency?

Effect of g on drops, particles and bubbles

$$\sum \tilde{F} = m\tilde{a}$$



$$\sum F = B - W \pm D + \ldots$$

Similarities:

- all are ***discrete phases*** surrounded by fluid
- all have ***buoyant forces*** acting on them (weight of displaced fluid)

Differences:

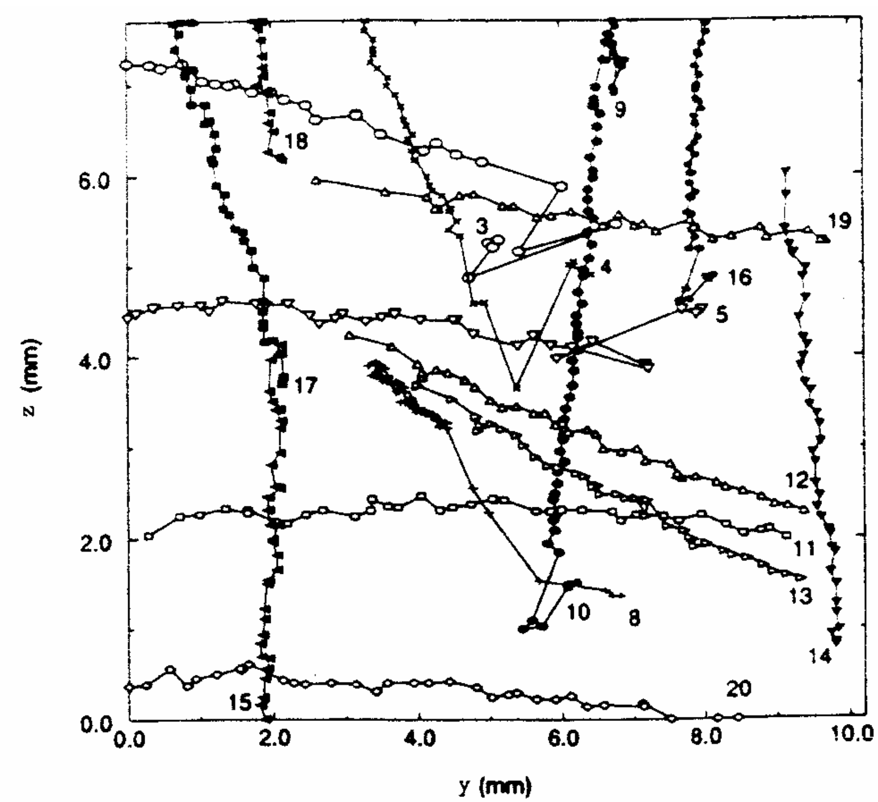
- ***different density ratios*** w.r.t surrounding fluid (**Drop**: $\rho_d>\rho_f$ **Bubble**: $\rho_b<\rho_f$ **Particle**: $\rho_p<\rho_f$ or $\rho_p>\rho_f$ or $\rho_p=\rho_f$)
- ***sign of drag force*** will be a function of ($\rho_l-\rho_m$), *l=b,d,p* (drag opposes direction of motion)
- ***response to applied shear and pressure forces*** (does it deform?)
- ***mobility of surface*** (can there be a velocity jump across the interface?)

Note: surface forces become more important with decreasing radius, acceleration, density variation

For further reading, see the excellent review by Michaelides (1997) and the book by Subramanian and Balasubramanian (2001)

Effect of quasisteady g on particles/bubbles

Particle trajectories on the Shuttle



Polystyrene particles of 200, 400, 600 μm in triglycerine sulfate on the Shuttle

- Sun et al. (1994)

Relevant studies on bubble/particle interaction and space data

Numerical/theoretical: Bunner and Tryggvason (1999, bubbles); Drolet and Viñals (1998, particle/wall); Ellison et al. (1995, particles/wall); Langbein (1991, bubbles)

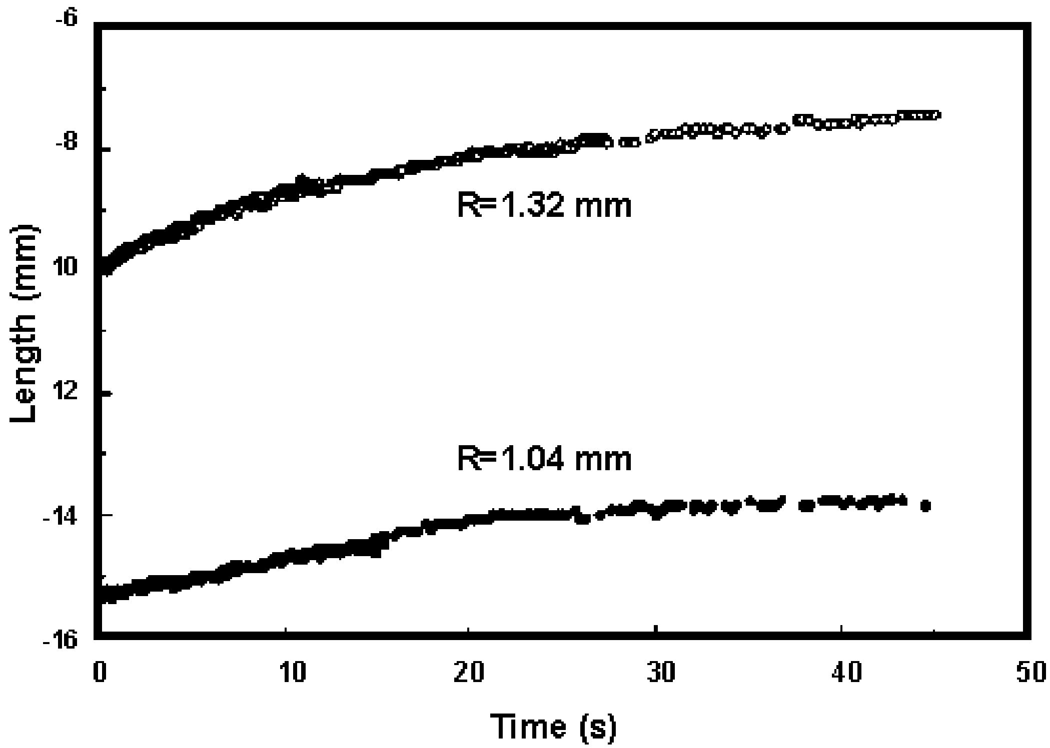
Experimental: Farris et al. (1998, bubbles); Kawaji et al. (1999, bubble); Ishikawa et al. (1994, bubble/wall); Tryggvason et al. (2001, particles); Trolinger (2000, particles); Ellison et al. (1995, particles); Langbein (1991); Sun et al. (1994, particles)

Theory says:

$$U_t \sim 2gL^2/9\nu$$

in the direction of g (for particles heavier than fluid medium)

Bubble motion in μg



Normal component of velocity of air bubbles in silicone oil near a wall on the Shuttle

- Ishikawa et al. (1994)

Theory says:

$U_t \sim 2gL^2/9\nu$

in the direction of –g

- In order to predict the discrete phase motion, one can employ:
  - ***creeping flow*** assumptions
  - ***finite Reynolds number*** approximations
  - ***semi-empirical*** equations

(see, e.g., Michaelides, 1997; Subramanian and Balasubramanian, 2001)

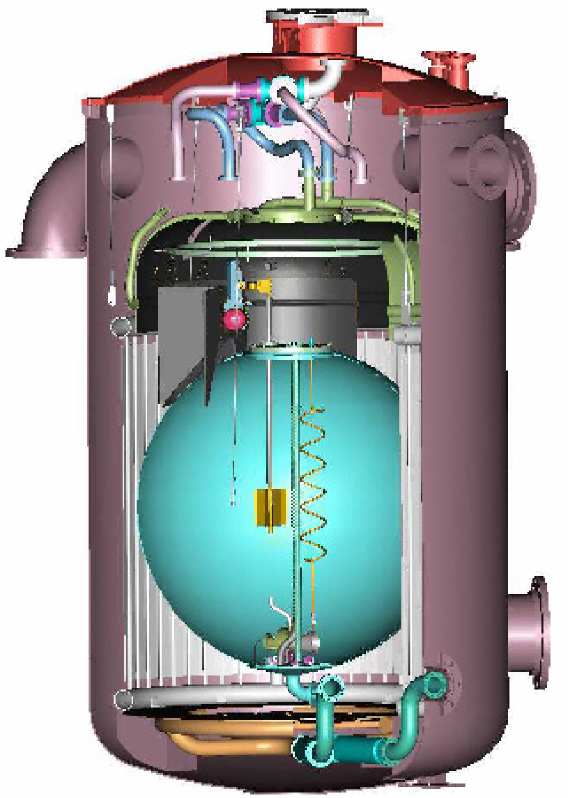
- ***Slow bubble drift*** apparent in Shuttle data, almost certainly in response to quasisteady g (Ishikawa et al.,1994; Farris et al., 1998)

- Analysis of particle/bubble motion is ***complicated by***:
  - ***wall effects*** and
  - ***interactions*** among bubbles/particles
  - lack of correlation to measured ***acceleration***

Gravitational effects in cryogenic fuel storage

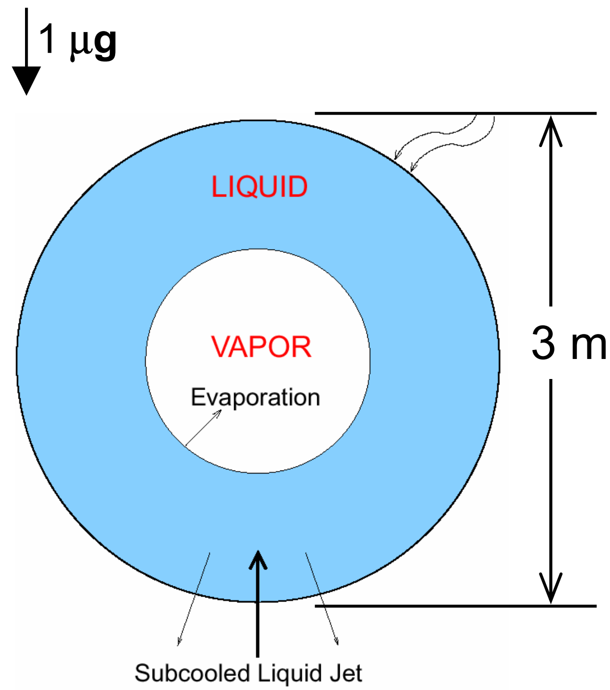
QUASISTEADY G

Prototype storage tank



Protoflight ZBO Development Ground Test

Numerical model of storage tank



Steady uniform heat flux (Q_T=2.8 W) at outer wall

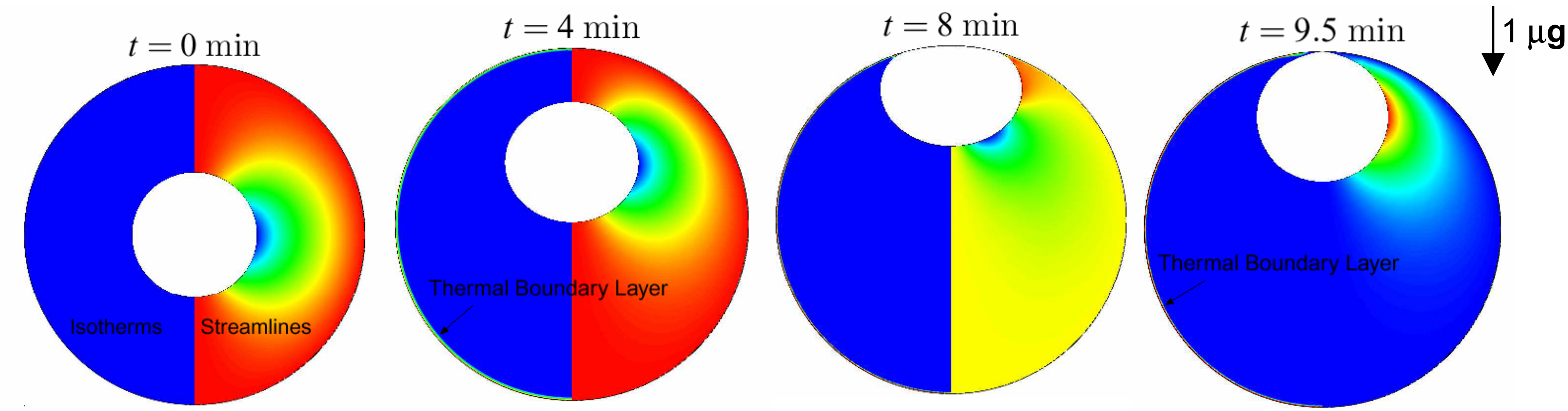
- During storage, cryogen vaporization is the main cause of tank ***pressurization*** and resultant ***mass loss***
- On earth, pressure is typically controlled by ***venting***, ***but***
- venting vapor in an enclosed spacelab may be ***hazardous*** and is ***wasteful***

GOAL: test a design concept using ventless methods to control pressure through experimental and computational methods

- Panzarella et al. (2004)

QUASISTEADY G

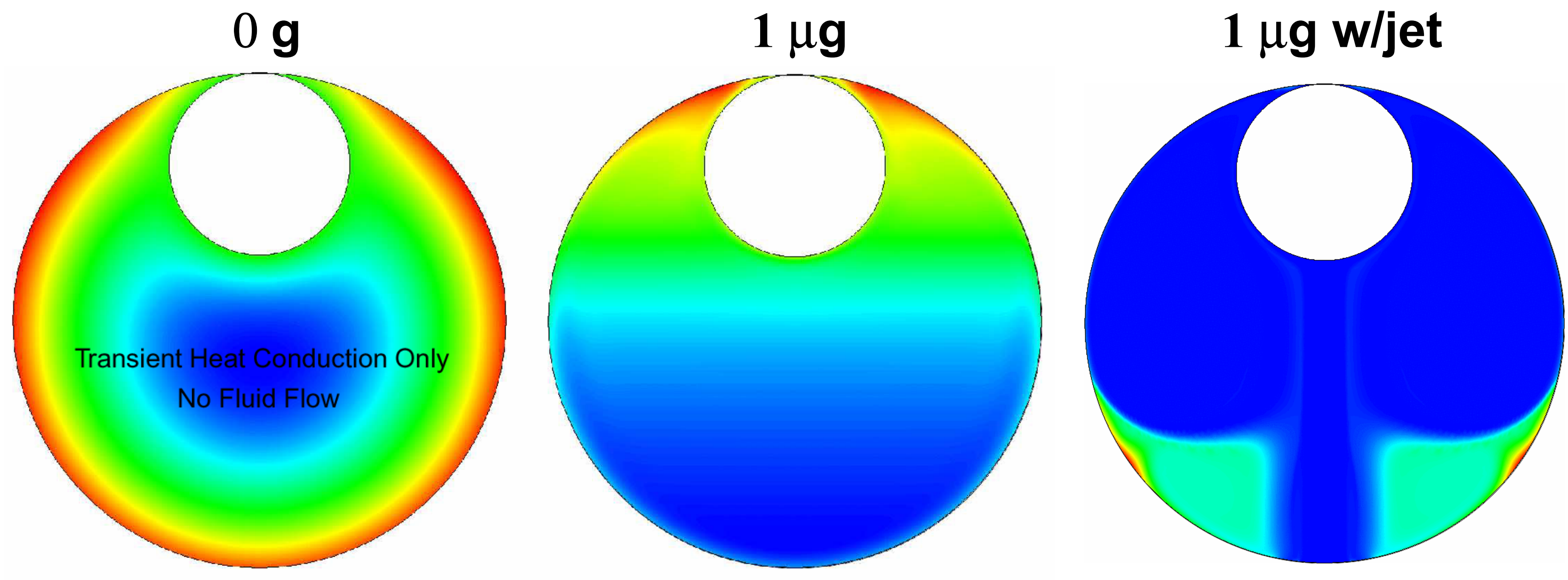
Cryogenic vapor bubble in a 95% full storage tank



- The conduction time scale for this large tank is about 6 days
- Bubble moves opposite to gravity
- It only takes 10 minutes for the bubble to reach the wall, boing, and return to spherical shape
- If g points in one direction for 600 sec or more, buoyancy can move the vapor region up to the "top"

QUASISTEADY G

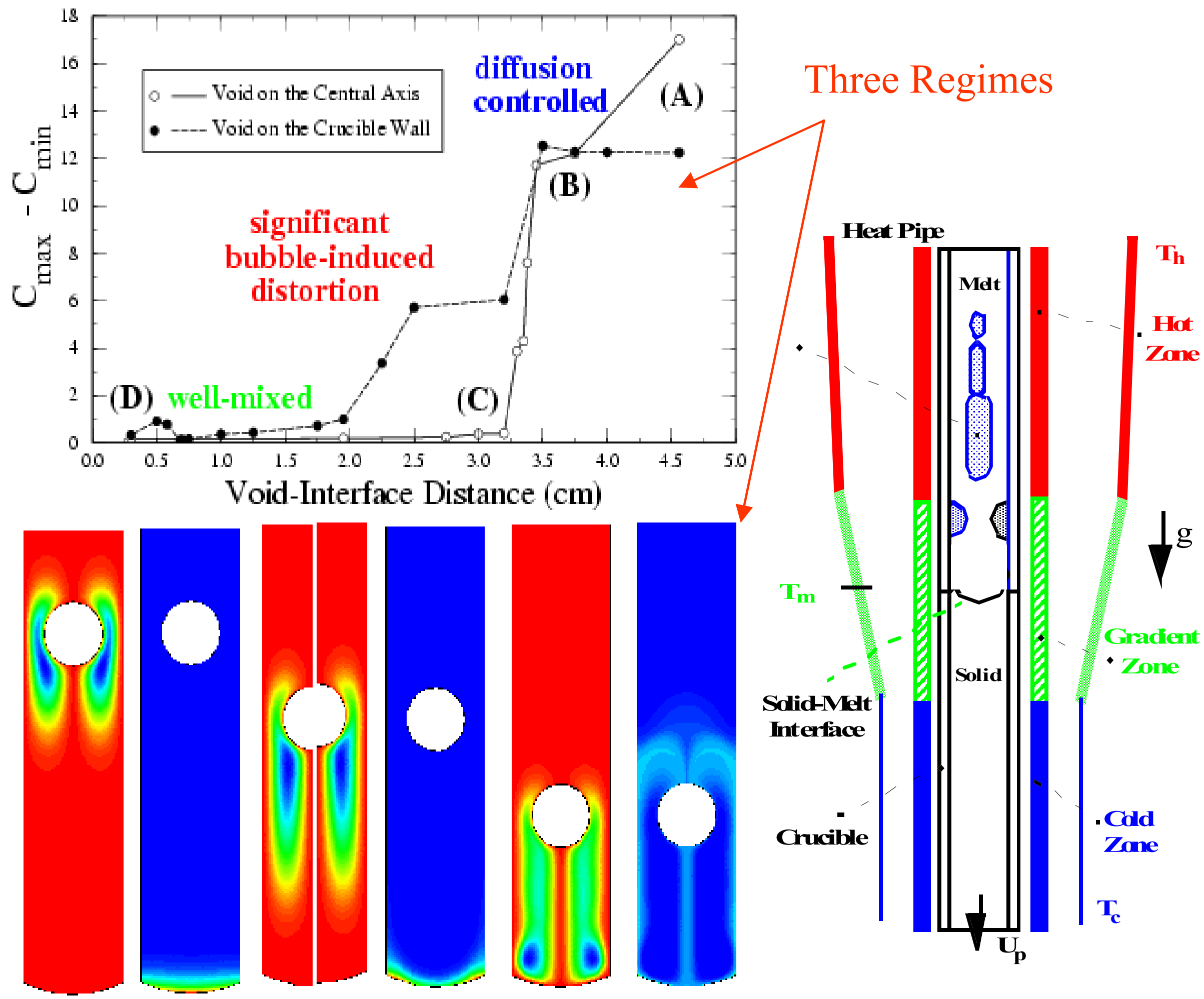
Comparison of 0g and μg temperature maps after 75 days



- μg exhibits stratified flow; its "hot spots" can lead to increased evaporation
- addition of jet flow at μg can isolate the hot spot that used to be near the bubble

Effect of Bubble-Generated Convection on 1g and Microgravity Transport Processes

QUASISTEADY G



- Three recent NASA microgravity experiments have been hampered by thermocapillary convection caused by unwanted voids and/or bubbles in the melt.
- Finite element analysis shows that ***void generated convection can affect radial segregation drastically***, especially, if the thermocapillary vortex penetrates the solutal boundary layer at the growth interface.
- From a transport point of view, ***three different regimes*** are identified based on the distance between the void and the growth interface.

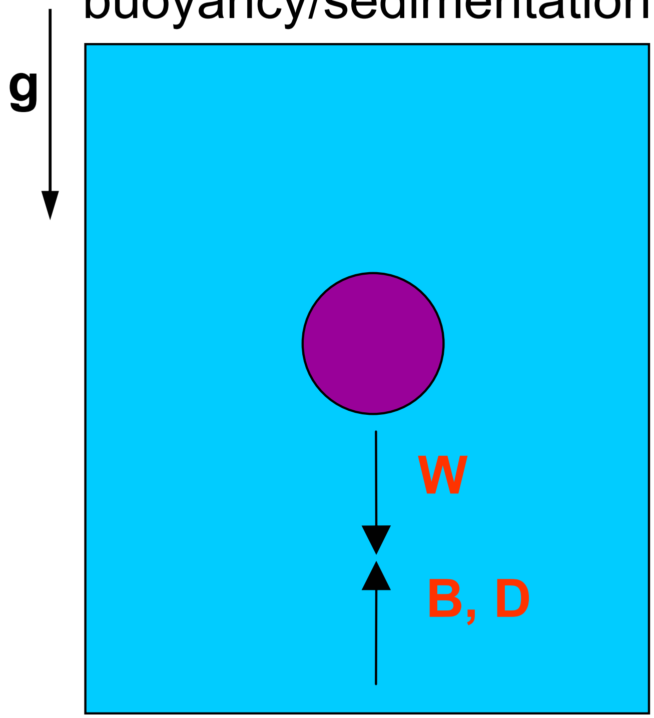
- Kassemi et al. (2000, 2001)

QUASISTEADY G

Newton's 2nd law (conservation of momentum)

PARTICLE / DROP / BUBBLE

buoyancy/sedimentation



$$\sum \tilde{F} = m\tilde{a}$$

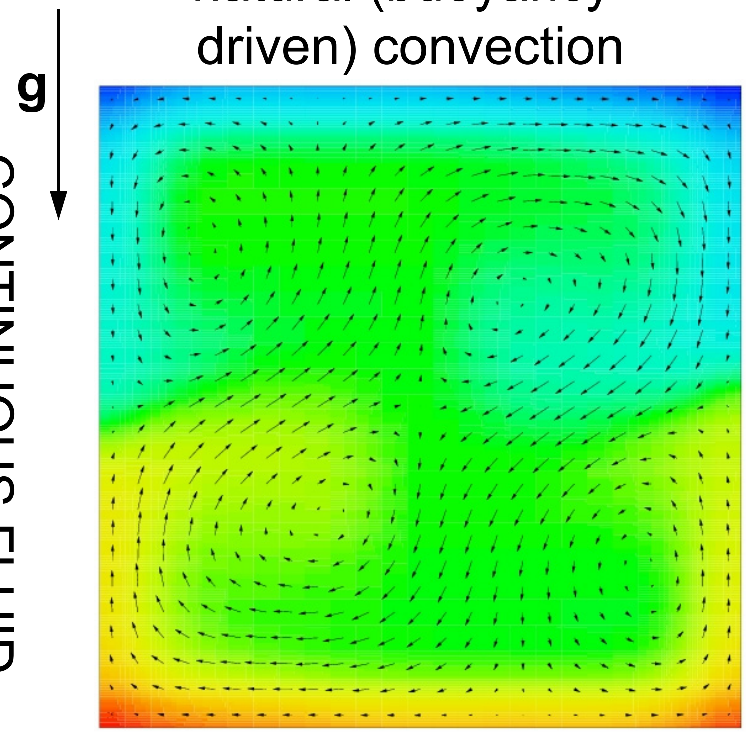
In the vertical direction, the dominant forces are:

$$\sum F = B - W \pm D + \ldots = ma$$

Forces **Reaction to forces**

CONTINUOUS FLUID

natural (buoyancy-driven) convection



$$\rho = \frac{m}{V}$$

$$\frac{\partial}{\partial t}(\rho\tilde{u}) + \tilde{u}\cdot\nabla(\rho\tilde{u}) = \nabla\cdot(\mu\nabla\tilde{u}) - \nabla p + \rho\tilde{g} + \ldots$$

Reaction to forces **Forces**

Governing equations for basic natural convection

For basic natural convection for Newtonian fluids with constant properties and no internal sources, we can write conservation of momentum, species and energy (using the Boussinesq approximation) as:

temporal change + convection = diffusion + source

momentum

$$\frac{\partial \tilde{u}}{\partial t} + \tilde{u} \cdot \nabla \tilde{u} = \nu \Delta \tilde{u} - \frac{1}{\rho_0} \nabla p + \beta \Delta T \tilde{g}$$

energy

$$\frac{\partial T}{\partial t} + \tilde{u} \nabla \cdot T = \alpha \Delta T$$

species

$$\frac{\partial C}{\partial t} + \tilde{u} \nabla \cdot C = D \Delta C$$

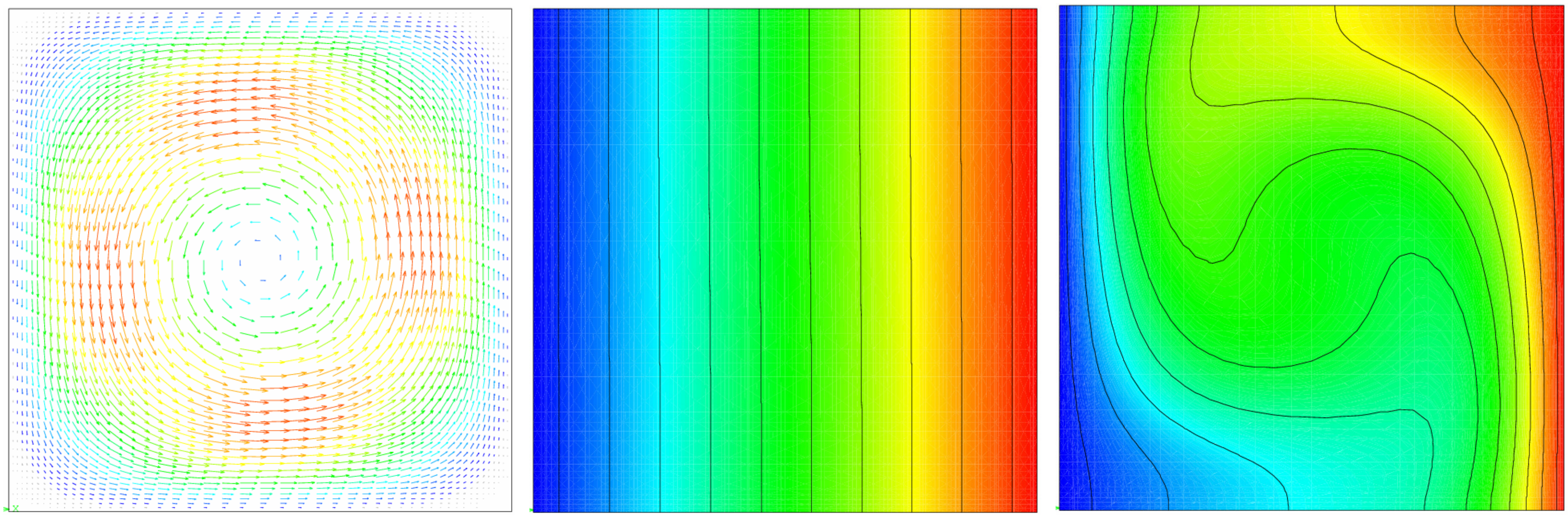
Applying scaling analysis to these equations make nondimensional numbers pop out

$$\Pr = \frac{\nu}{\alpha} \qquad Sc = \frac{\nu}{D}$$

Prandtl number Schmidt number

Example: natural convection in a molten semiconductor

QUASISTEADY G



g

Velocity Temperature Species

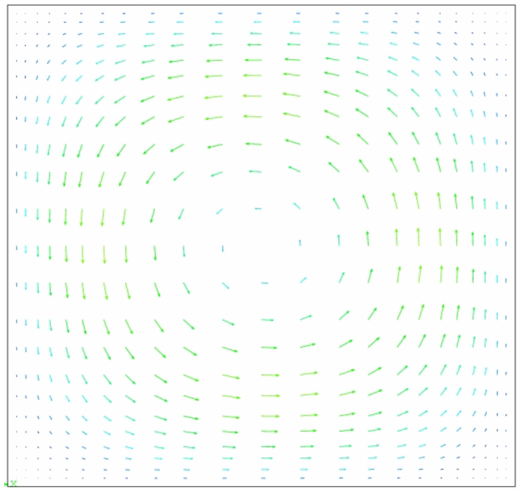
Se in GaAs

Ratio of momentum diffusion to thermal diffusion is small: **Pr = ν/α = 0.01**

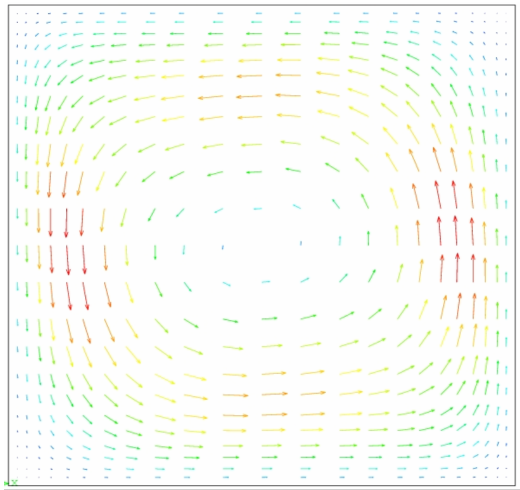
Ratio of momentum diffusion to species diffusion is large: **Sc = ν/D = 30**

Effect of g magnitude on velocity field

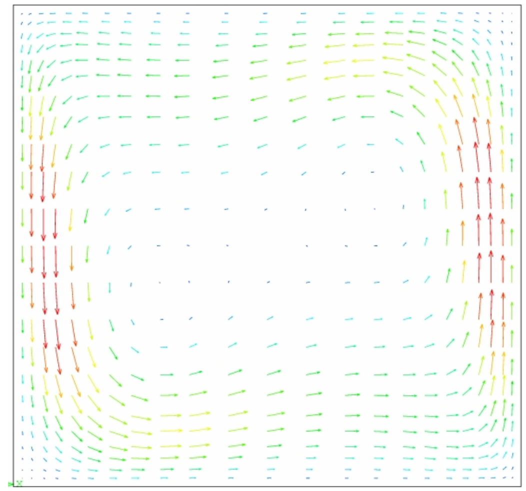
QUASISTEADY G



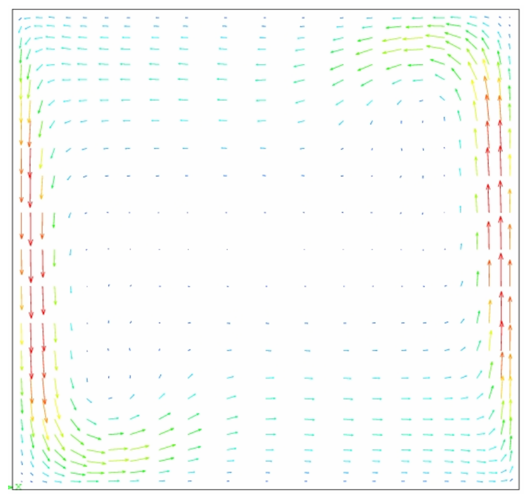
Ra=1e3



Ra=1e4



Ra=1e5



Ra=1e6

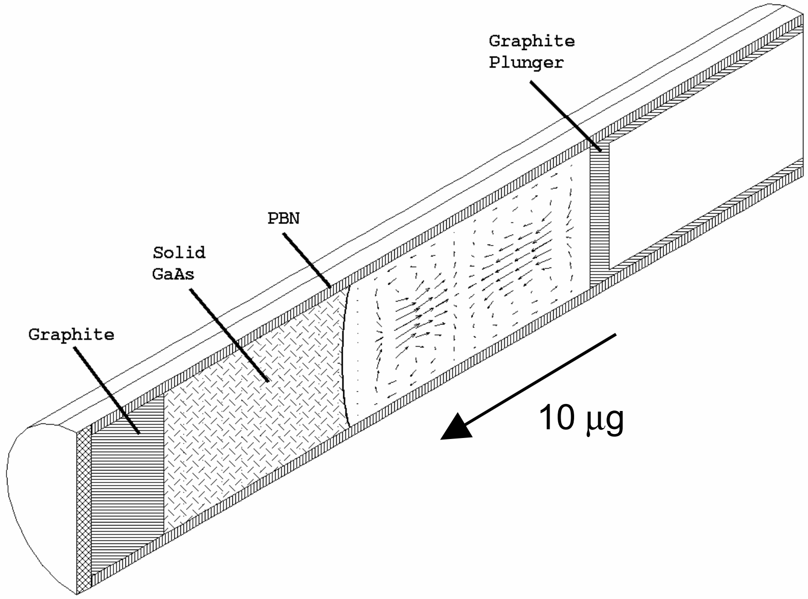
g

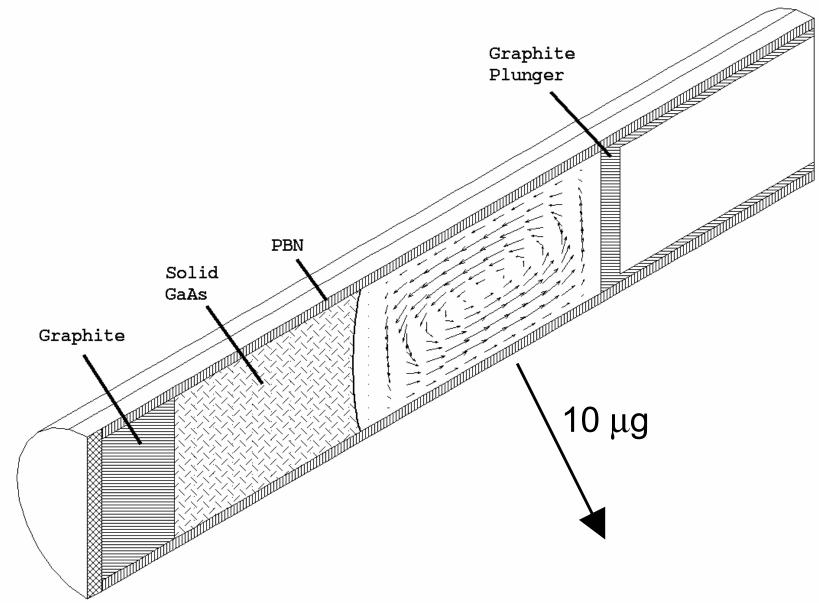
$$Ra = g\beta\Delta T d^3 / \nu\alpha$$

Increasing the Rayleigh number can increase flow intensity ***and*** change flow mode

Effect of quasisteady g orientation on natural convection

Directional solidification of GaAs

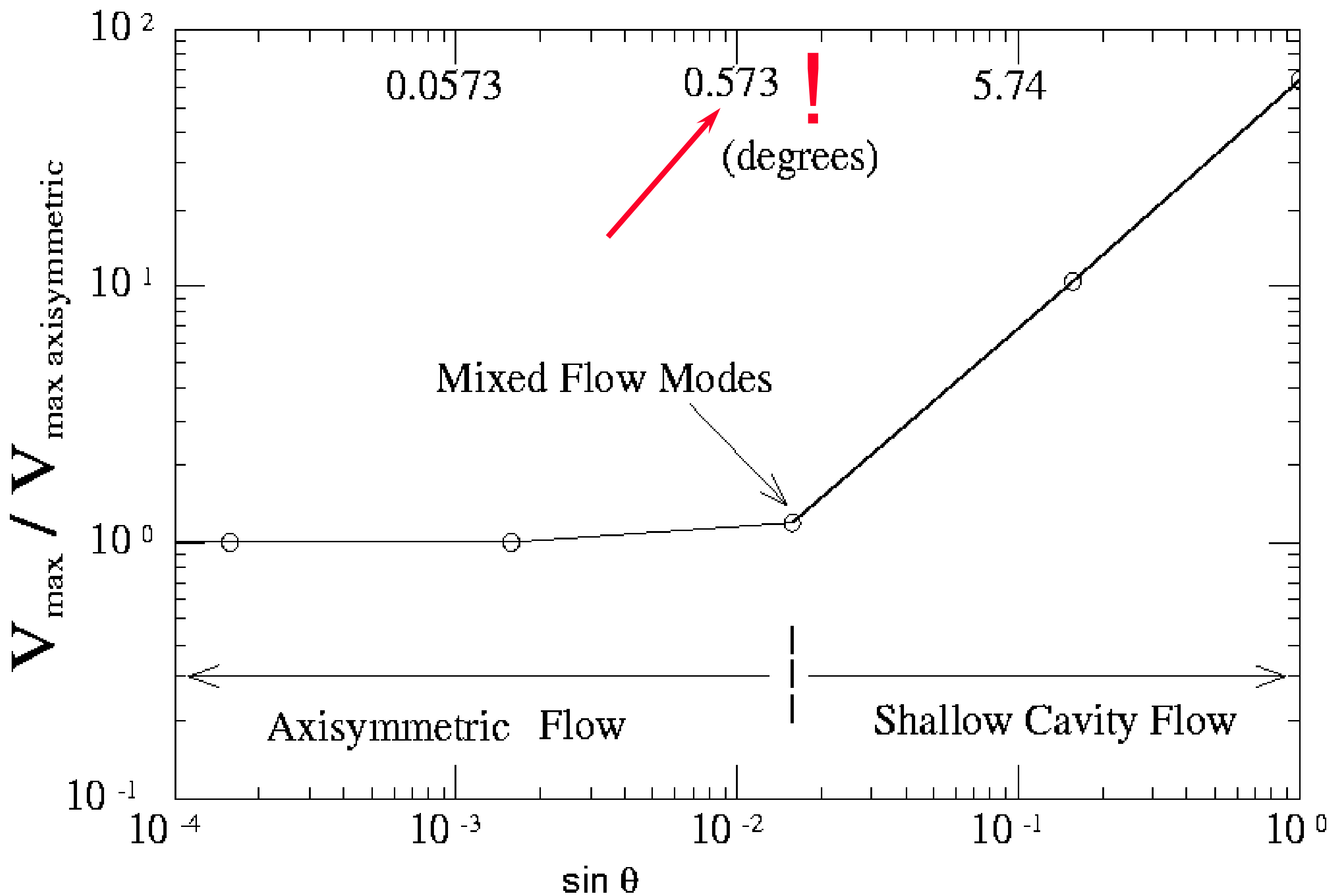




Orientation of g can cause different flow modes with increased/decreased convective intensity and variation in far-field mixing

- Arnold et al. (1991)

Sensitivity of directional solidification to quasisteady g orientation



Be aware that any inhabited spacelab is likely to be ***extremely*** variable in θ due to the rich variety of acceleration sources!

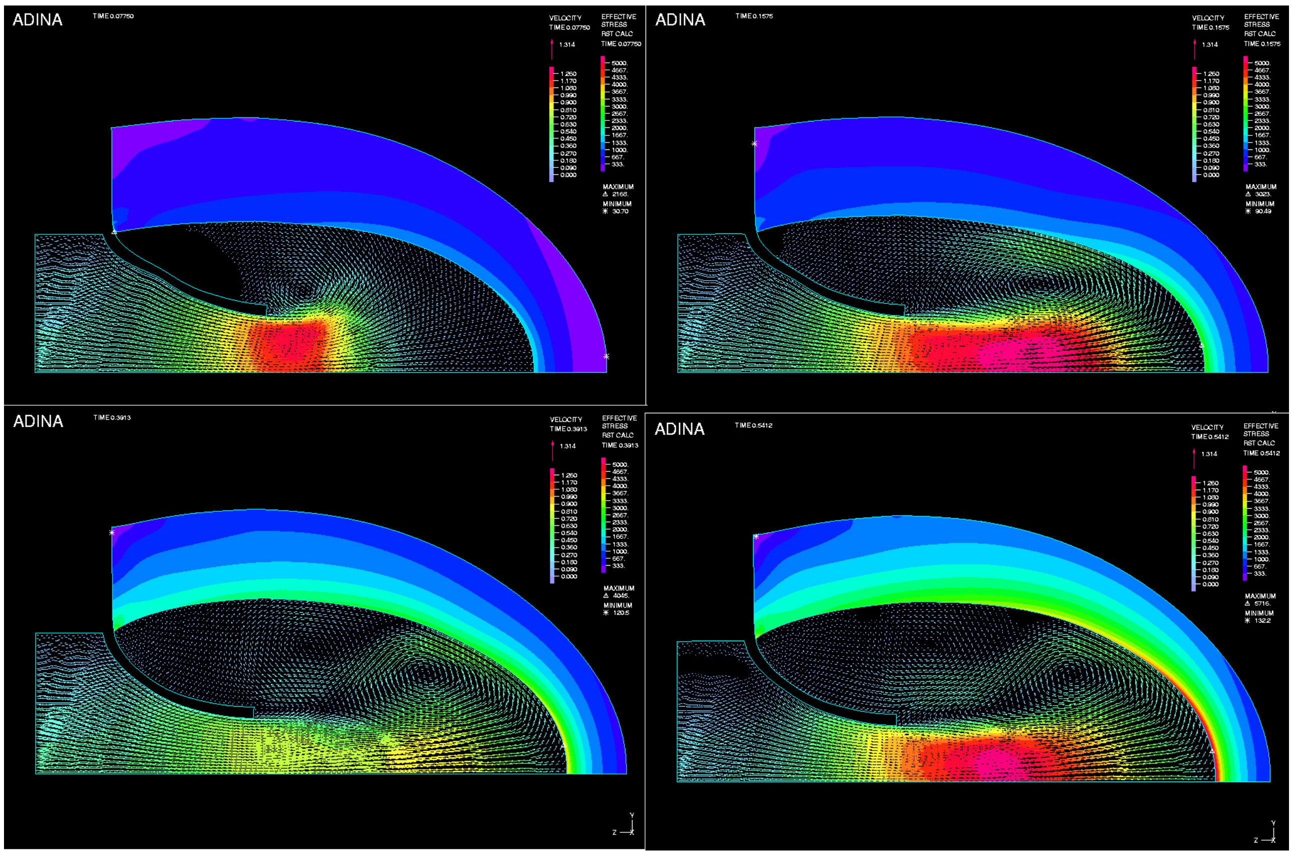
NOTE: For other experiments, this tendency towards improved mixing may actually be beneficial!

- Arnold et al. (1991)

Variable Gravity Fluid-Structural Behavior of The Heart

QUASISTEADY G

Flow & Stress During 1G Diastolic Expansion of Left Ventricle



- Deserranno et al. (2003)

Objectives:

• Study the intricate variable gravity Fluid-Structural Interactions (FSI) of the heart by element model of the ***left ventricle, left atrium*** developing a state-of-the-art 3D finite and the ***mitral valve*** in conjunction with animal experiments, 3D MRI cardio-imaging, and clinical case studies.

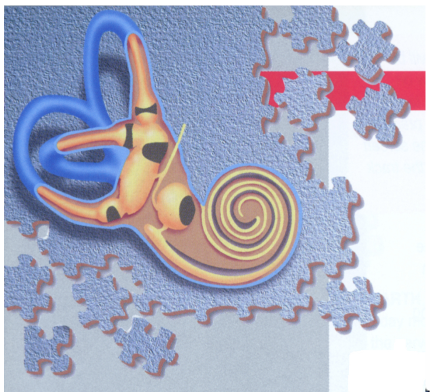
• Understand how ***lack of pericardial constraint in space*** can lead to ***increase in acute ventricular compliance*** to pressure and how cardiac atrophy in microgravity can lead to ***orthostatic intolerance*** - develop strategy for effective countermeasures.

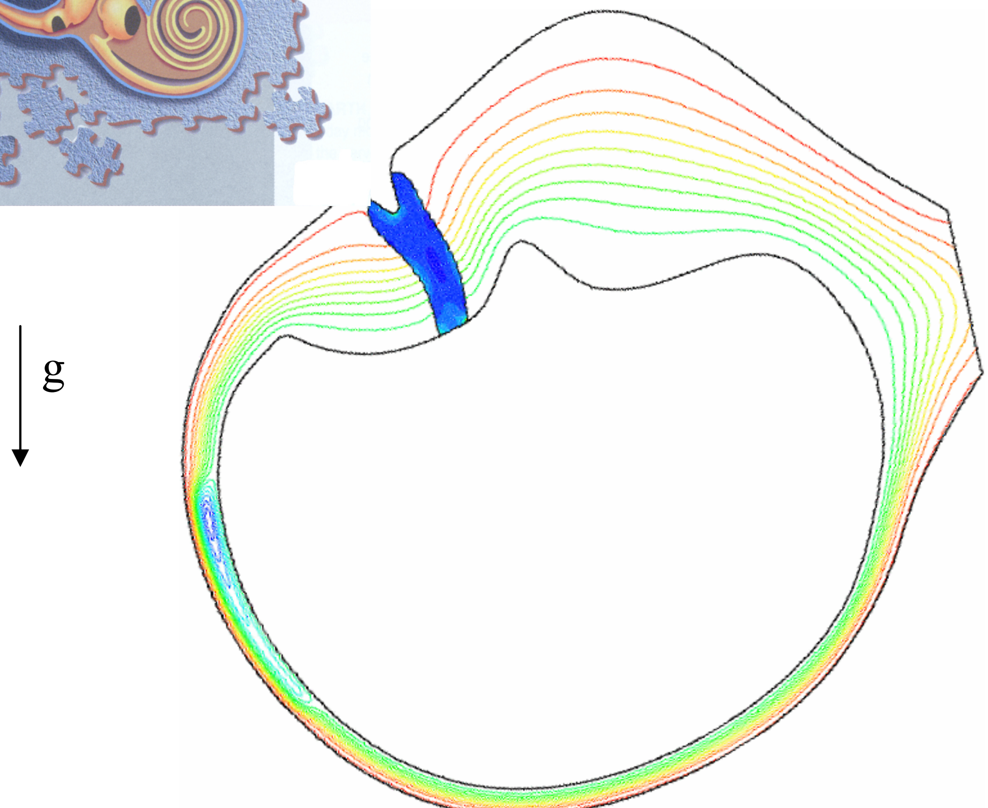
• Determine the feasibility of using IntraVentricular pressure gradients as markers for early detection of ***diastolic dysfunction preceding congestive heart failure*** on earth.

Gravitational fluid dynamics of the inner ear

QUASISTEADY G

Flow Bending the Cupula Partition during
1g Caloric Test





- Kassemi et al. (2003)

Objectives:

• Study the fluid-structural interactions (FSI) in the Semi-Circular Canal (SCC) System of the inner-ear under 1g, weightlessness, and artificial gravity conditions of Short Arm Centrifuge

• Recommend countermeasures based on first principal physics to reduce the risk of vestibular disorders arising from exposure to microgravity.

• Delineate the physical mechanisms responsible for common vestibular problems on earth such as Benign Paroxysmal Positional Vertigo or Unilateral Vestibular

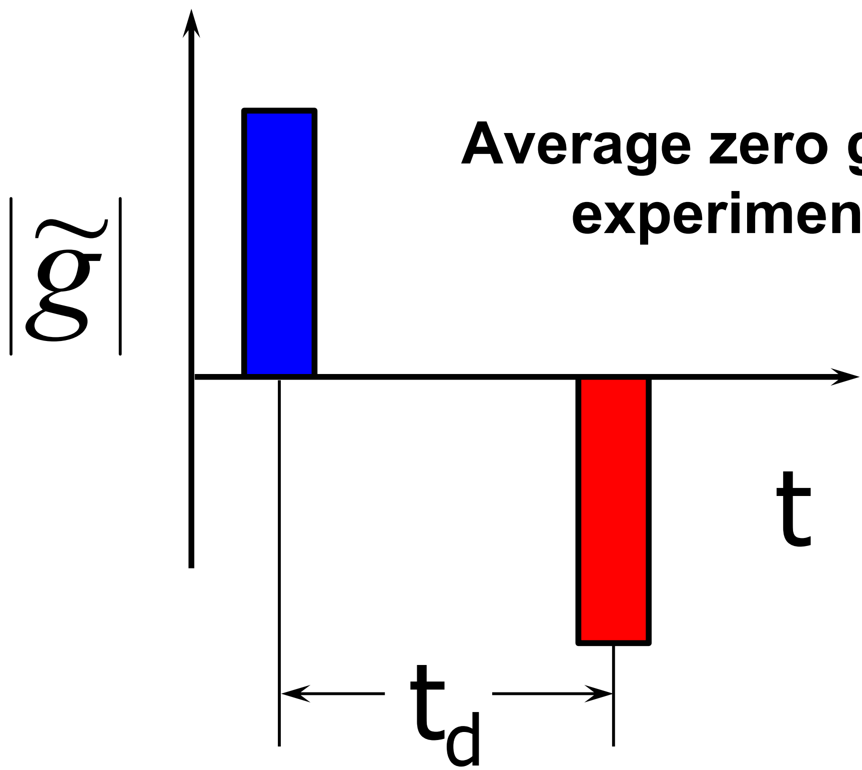
Results:

• Numerical simulations were performed which for the first time ***clarified the fluid physics responsible for the contradicting results*** of the microgravity caloric experiments aboard SkyLab.

Effect of transient g, g_t

- Transient accelerations are of ***short duration*** by definition (<1 s to several seconds, typically)
- Causes are such things as: thruster firings, hab soars, and crew activity, e.g., hammering
- Effects can ***dissipate with distance*** from the source
- Researchers must consider effect of:
  - impulse ***magnitude*** and ***duration*** (or a combination of the two)
  - ***orientation*** of impulse
  - ***time delay*** between impulses

Effect of transient impulses



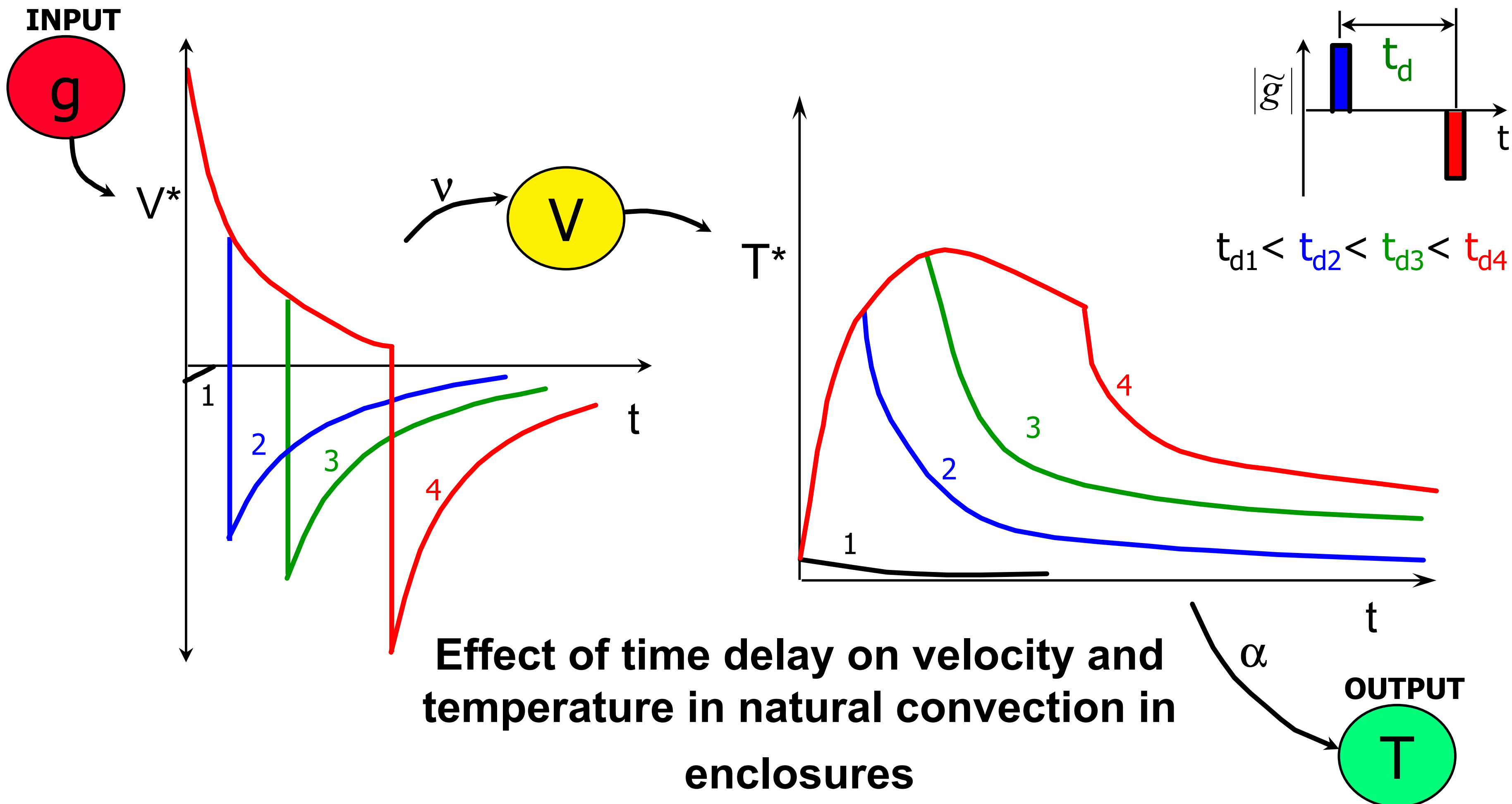
Average zero g ≠ zero effect on experiment necessarily

Net acceleration=0, *but* system reacts in a *transient* manner with finite response time

⇒ **Net system response may be nonzero**

Effect of transient pulse/antipulse (cont'd)

TRANSIENT G



Effect of time delay on velocity and temperature in natural convection in enclosures

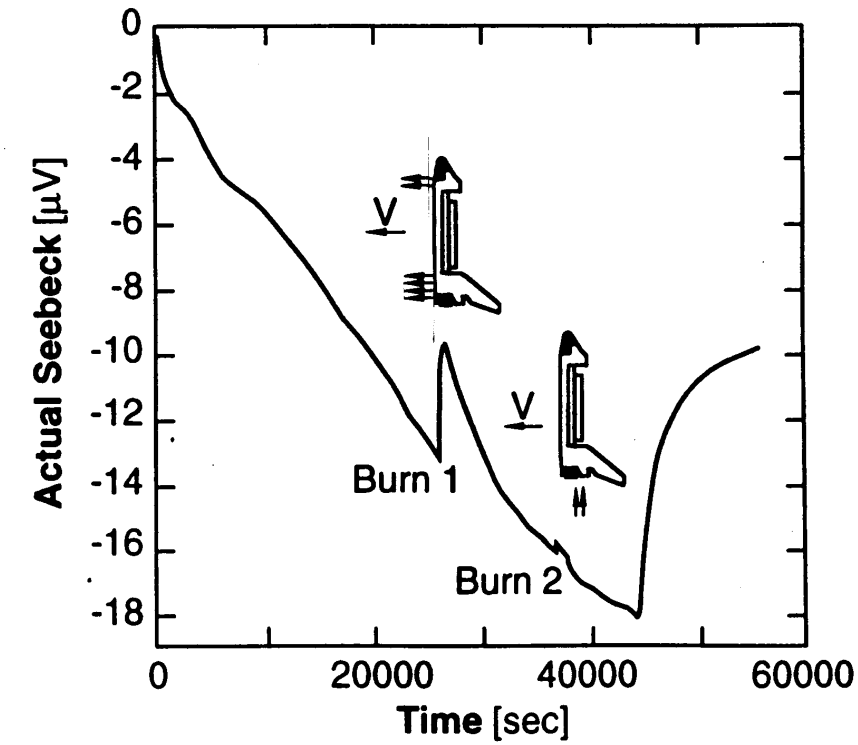
NOTE: Especially important for high Pr or Sc number flows

- Monti et al. (1990)

($Pr = \nu / \alpha$, $Sc = \nu / D$)

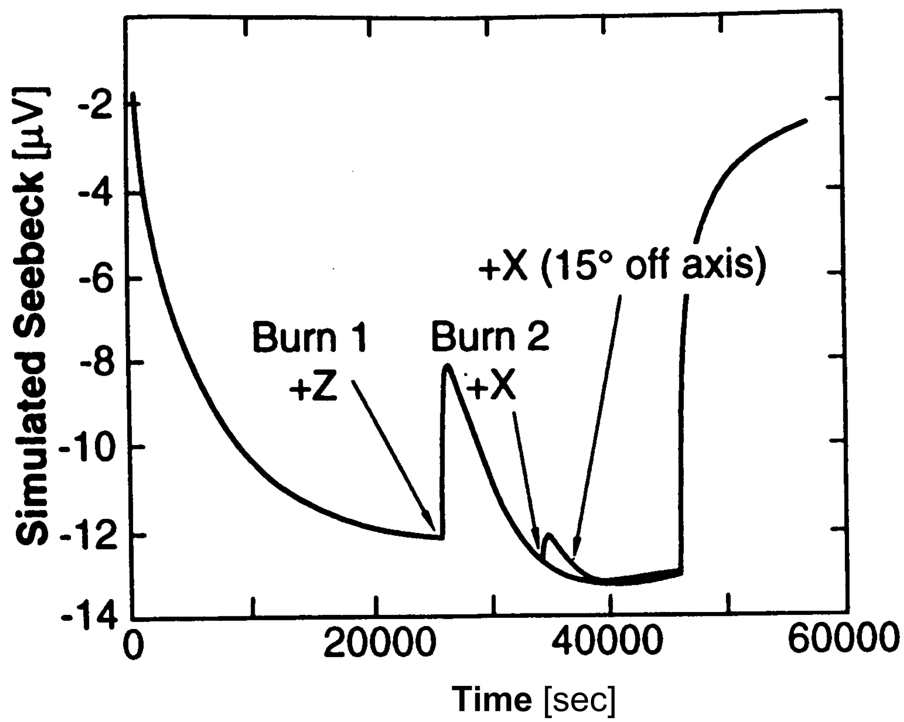
Effect of PRCS thruster burns on directional solidification (MEPHISTO)

TRANSIENT G



Results from MEPHISTO experiment

- Favier et al. (1994)

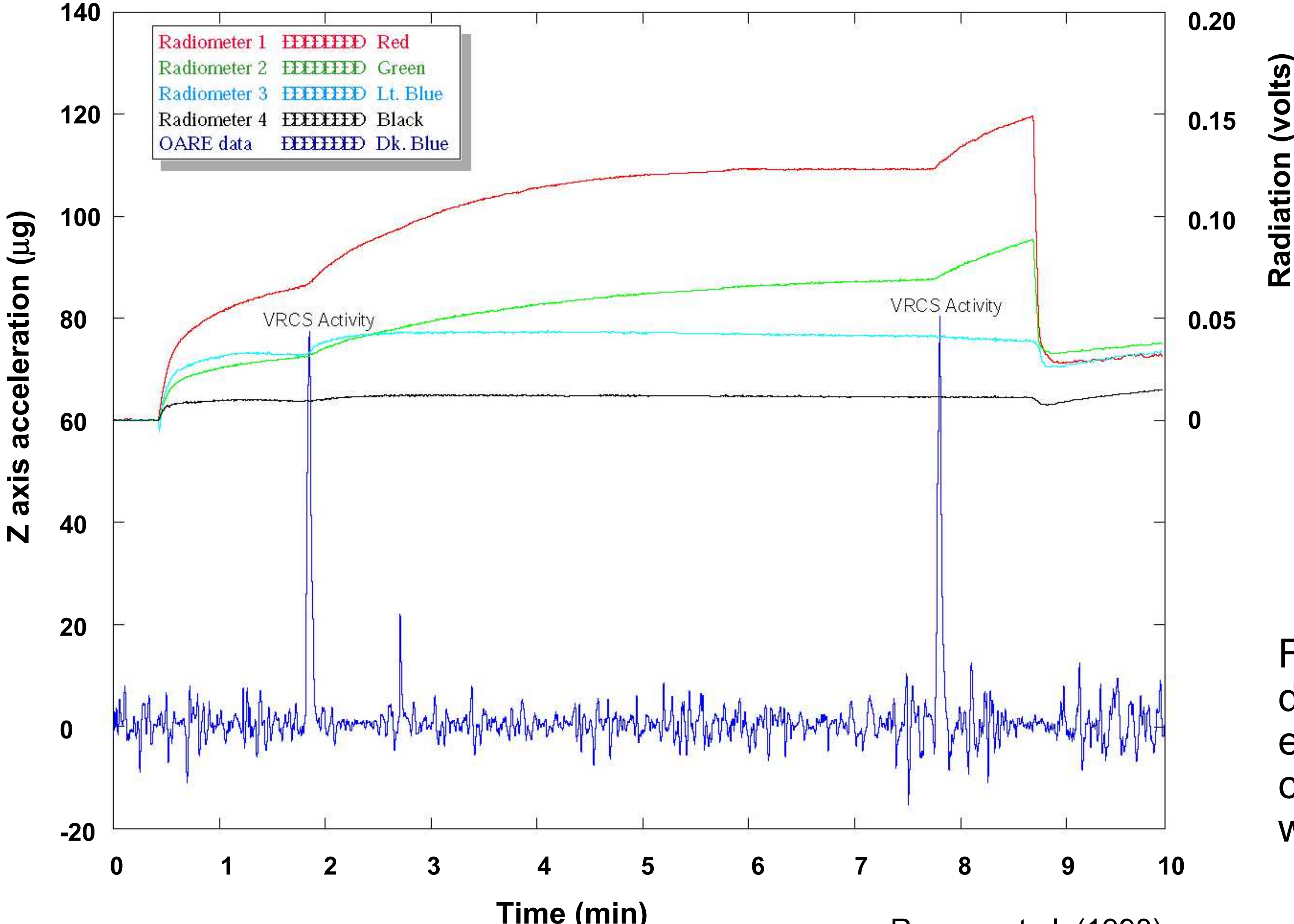


Results from MEPHISTO numerical model

- Alexander et al. (1997)

Note: Seebeck voltage is proportional to the solid/liquid interface temperature

Effect of VCRS burns on flame balls (SOFBALL)



For a general discussion of g-jitter effects on combustion, start with Ross (2001)

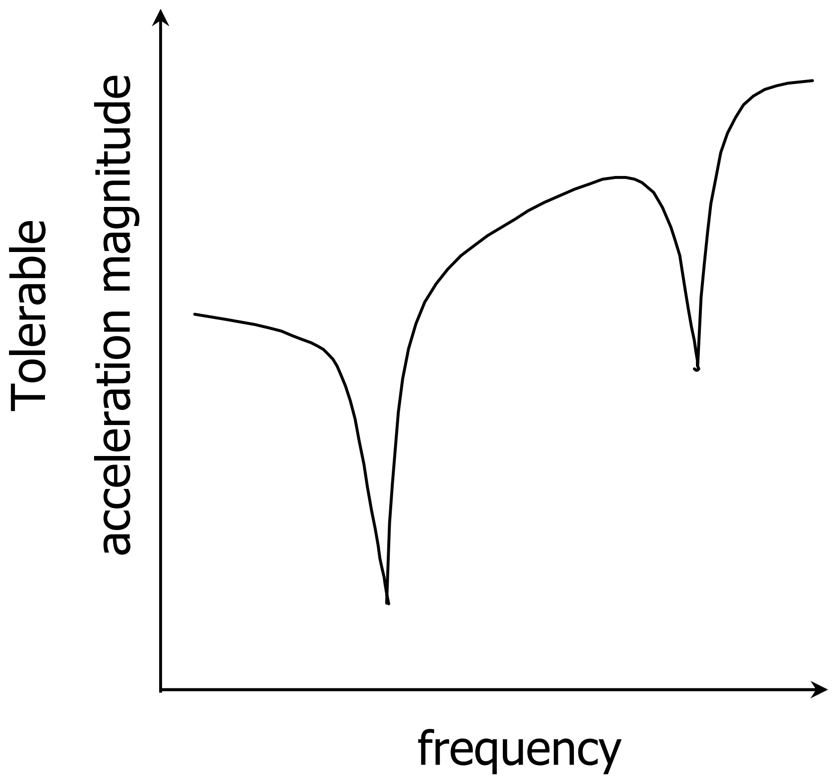
- Ronney et al. (1998)

Effect of oscillatory g, g_{osc}

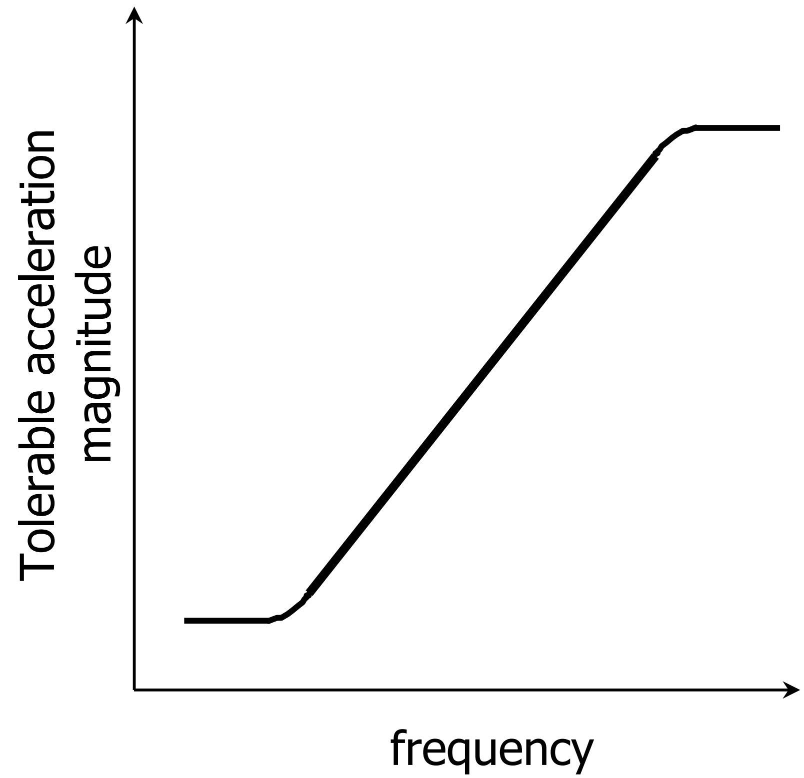
- ***Rich frequency content*** on ISS and Shuttle arising from structural oscillation, crew exercise, equipment operation
- Oscillatory g ***will vary from lab to lab*** on the ISS; it will depend on the disturbances that are ***present*** and the ***experiment proximity***
- Researchers must consider ***experiment sensitivity*** to oscillatory g:
  - ***particular frequencies***? Limitations on ***bulk flows*** generated from all of the frequency components?
  - ***amplitude*** of g (upper and lower thresholds)
  - ***orientation*** of g (expected to be highly variable due to variety of sources)
  - crew ***scheduling***?

OSCILLATORY G

Experiment response to oscillatory acceleration input



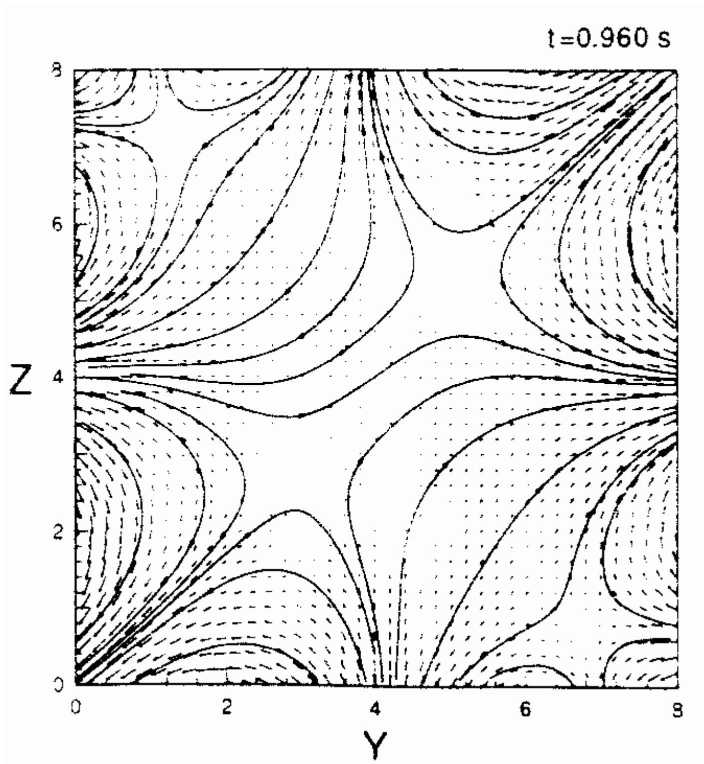
liquid bridges

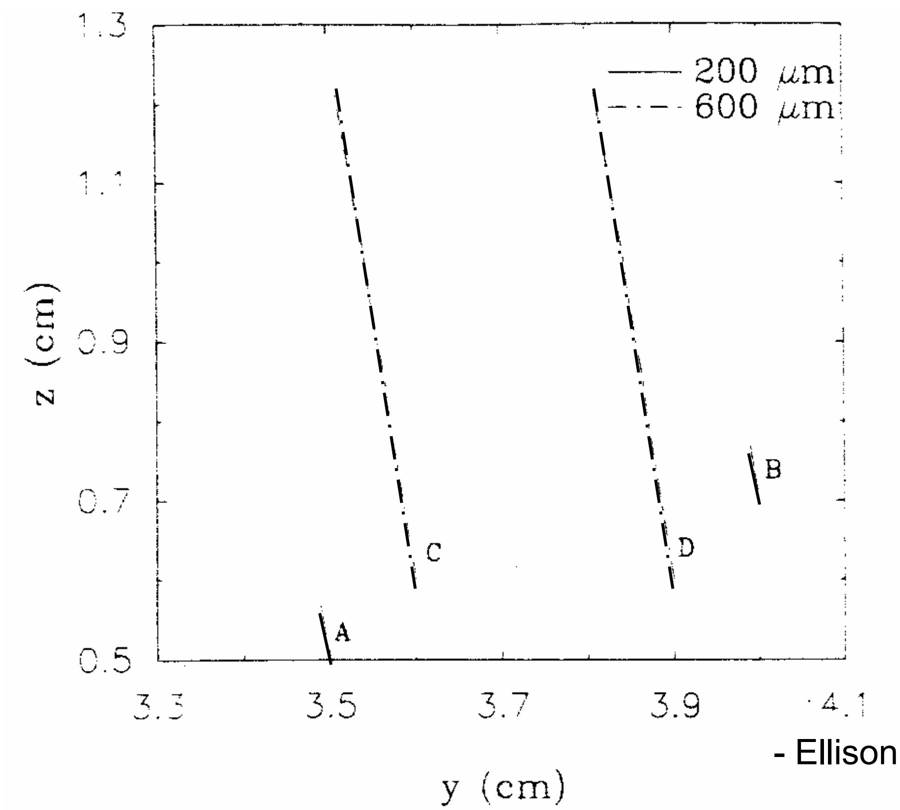


natural convection

- For example, see Nelson (1991), Alexander et al. (1990), Benjapiyaporn et al. (2000)

Body force vs. boundary vibration



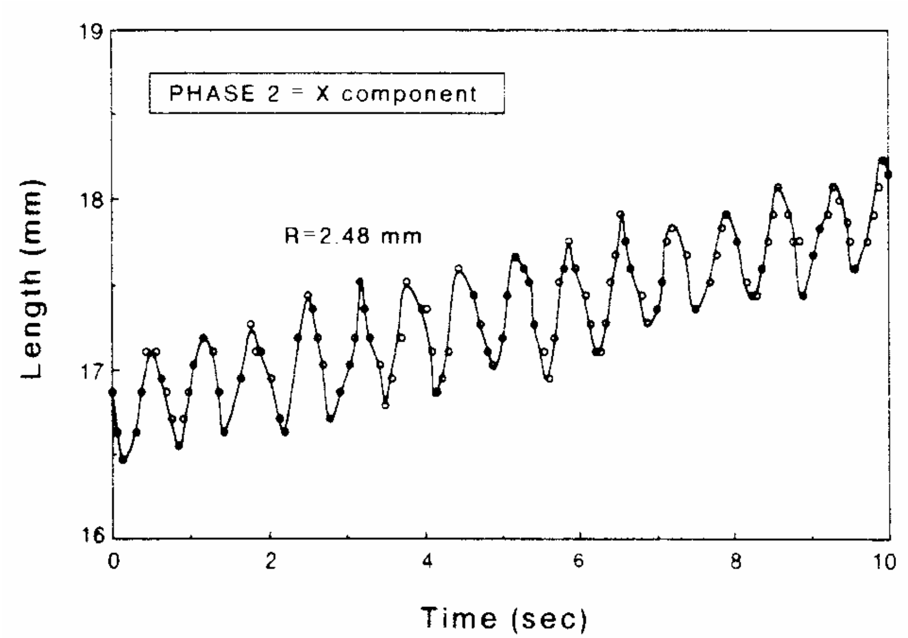


- Ellison et al. (1995)

In a 2D numerical simulation of particles and liquid in a container with ***flexible boundaries***, Ellison et al. (1995) found that transient bulk flows could be generated by Shuttle-type g-jitter. ***Particles in the same plane moved in parallel***.

Studying fluid near a boundary, Volfson and Viñals (2001) found that ***random vibration of boundaries*** can lead to ***diffusion layers*** that are larger than that of pure sinusoidal vibration.

Effect of oscillatory acceleration on bubbles



- Ishikawa et al. (1994)

Oscillatory response of a bubble in silicone oil to controlled sinusoidal forcing on the Shuttle

$$x(t) = \frac{6\nu A}{2\pi f}\sin(2\pi f t) - R^2 A\left[\cos(2\pi f t) - \exp\left(-\frac{6\nu}{R^2}t\right)\right]$$

where $A = \dfrac{2R^2 g_{osc}}{36\nu^2 + R^4 (2\pi f)^2}$

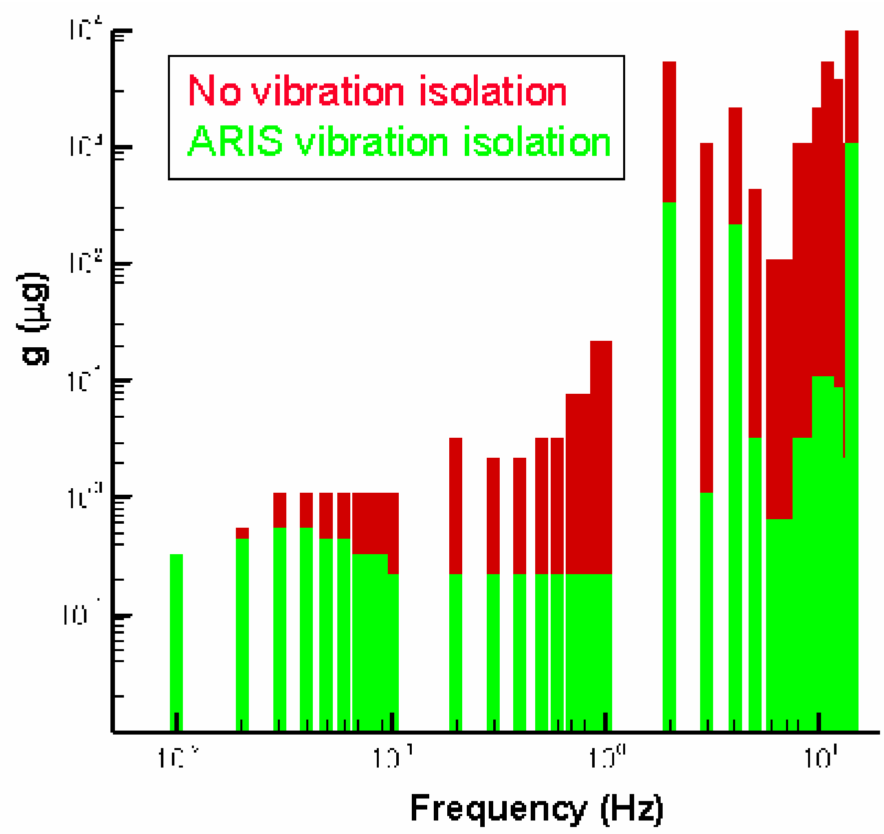
- On the Shuttle, 2-5 mm air bubbles were injected into silicone oil and subjected to a controlled sinusoidal oscillation
- Note ***upward drift due to quasisteady acceleration***
- Theoretical and experimental prediction of bubble position are good. Correlation weakens when:
  - bubbles are near a ***wall***
  - ***more bubbles*** are added to the fluid
  - bubble ***size increases***

- Ishikawa et al. (1994)

- ***Wall effects*** on bubble motion, response to oscillatory forcing and to background g were also noted by Farris et al. (1998); also see Kawaji et al. (1999).

OSCILLATORY G

Effect of vibration isolation on natural convection



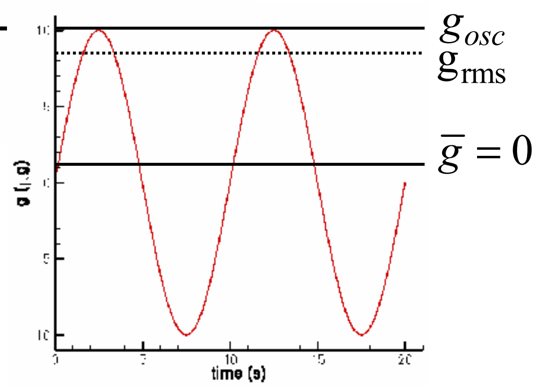
- Nelson and Kassemi (1997)

Idealized ISS environment:

- constructed from DAC-3 (Design Analysis Cycle #3)
- used a frequency range from 0.01 to 14 Hz for several hours of simulated μg

Use this data to create g(t):

$$g_i(t) = g_{qs,_i} + \sum_n g_{o,_i} \sin(2\pi f_n t)$$



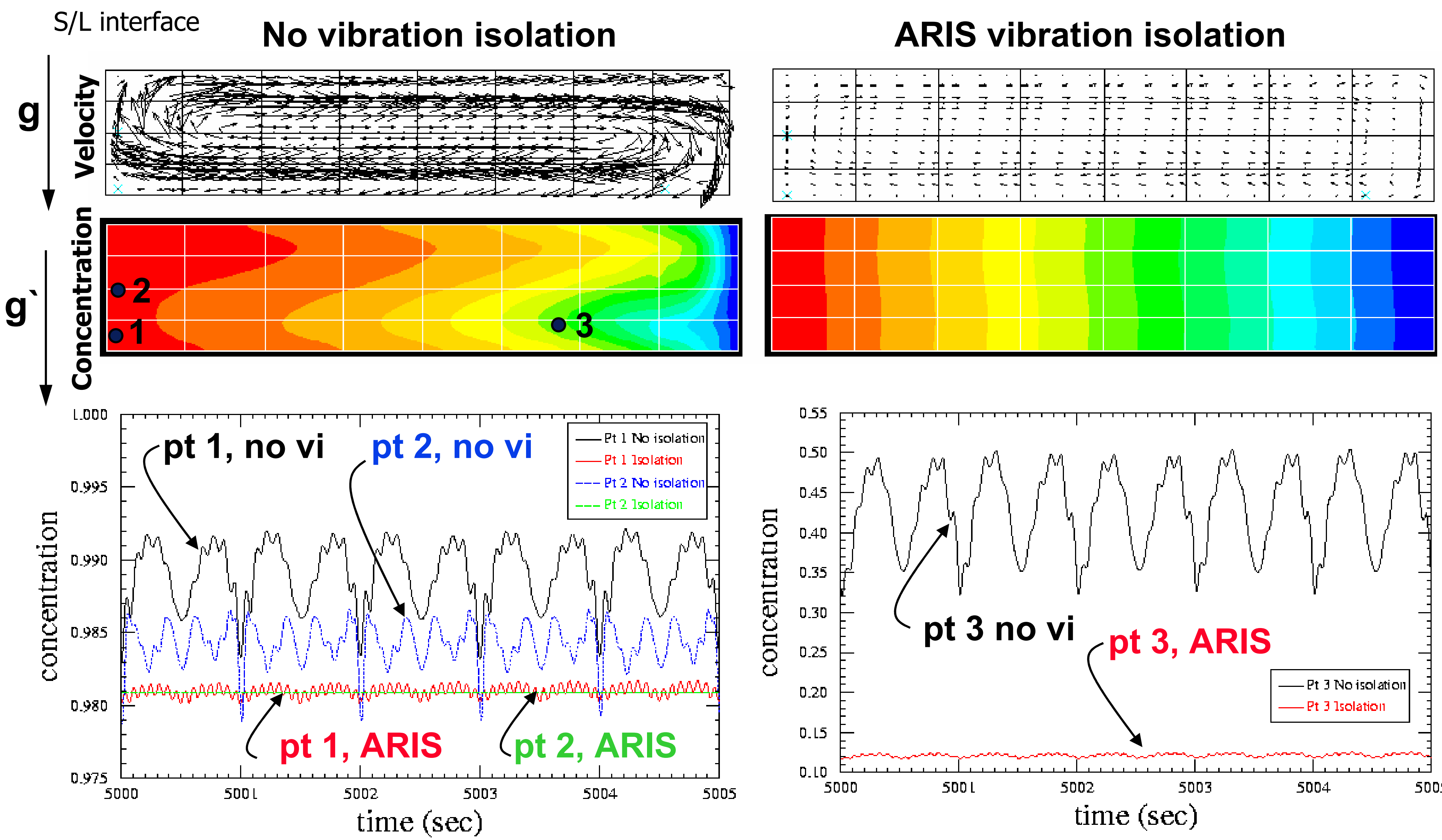
Reminder:
For a pure sinusoid,

$$\bar{g} = 0 \text{ but}$$

$$g_{rms} = \frac{\sqrt{2}}{2} g_{osc}$$

Effect of vibration isolation on natural convection (cont'd)

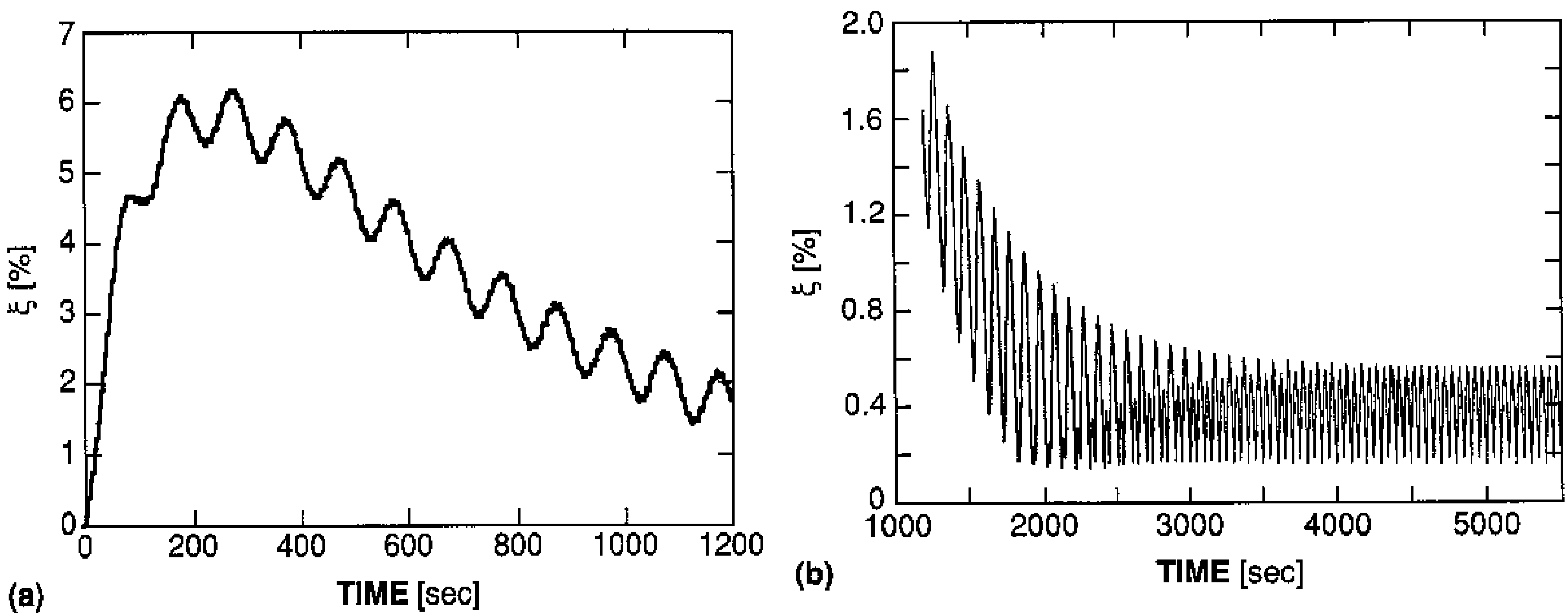
OSCILLATORY G



- Nelson and Kassemi (1997)

OSCILLATORY G

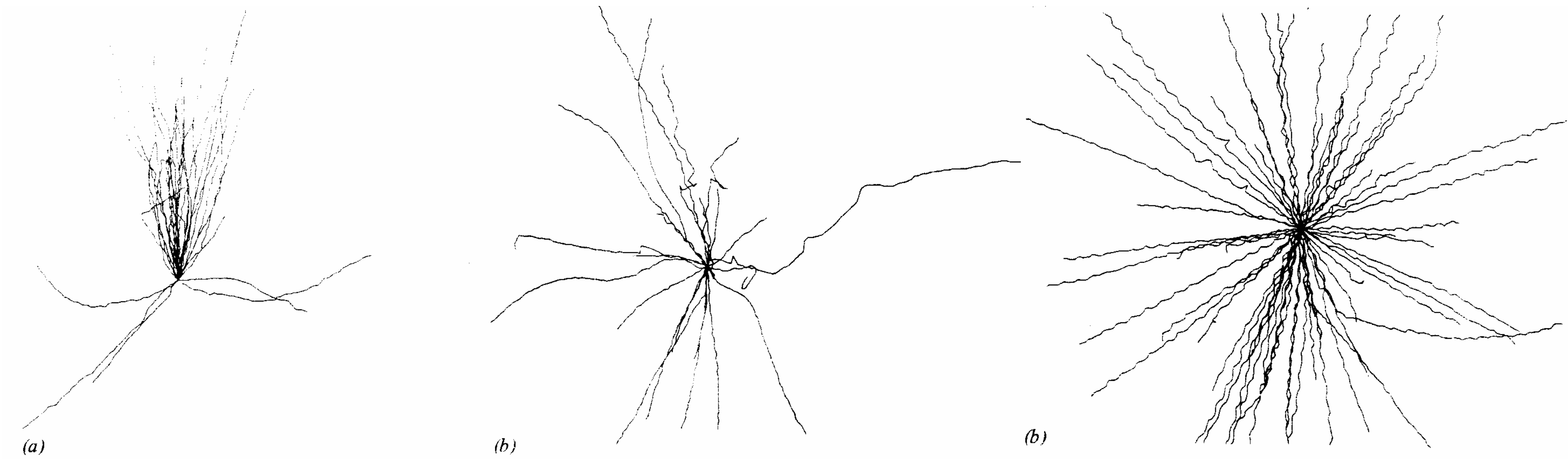
Initial transient in natural convection in enclosures: Startup of multifrequency sinusoidal disturbance



Concentration variation at solid/liquid interface as a function of time using a simplified spectrum of the Shuttle acceleration environment exhibits startup phenomenon

- Alexander et al. (1991)

Effect of g on tracks of *Euglena gracilis*



1g	μg	clinostat
		(“simulated μg”)
		- Vogel et al. (1993)

Wiggles in clinostat traces are undoubtedly caused by variation in ***g orientation***

Modulation in g magnitude should produce correlated ***modulation in velocity*** for microbes exhibiting gravikinesis

Conclusions

Space experiments typically occur in a more complicated acceleration environment than that on earth.

- A known, steady acceleration environment is substituted for an acceleration environment that is ***not known*** *a priori* and varies significantly in terms of ***magnitude***, ***orientation*** and ***frequency*** content
- More familiar phenomena driven by, e.g., buoyancy-driven convection, are ***dominated by less familiar forces***, e.g., surface tension, radiation heat transfer, wall effects, etc.

Nevertheless, there are things we can say with respect to the hydrodynamic effects of the microgravity environment and its effects on continuous fluids with density gradients and embedded discrete phases (bubbles, drops, particles) within fluids

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