Section 9.
Developing microgravity tolerance specifications

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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	diameter
D	drag
D_C	diffusivity of species
D_m	mass diffusivity
F	force
g	gravity
k	thermal conductivity
L	characteristic length scale
m	mass
p	pressure
Pr	Prandtl number $=\nu/\alpha$
S	source term
Sc	Schmidt number $=\nu/D$
t	time
T	temperature

Roman characters (cont'd)

u	velocity
$\forall$	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

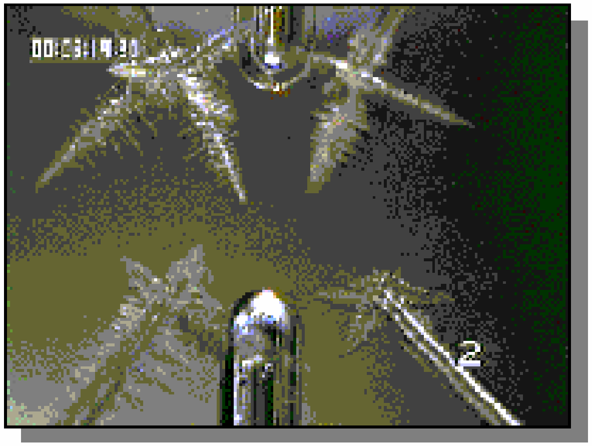
b	bubble
d	droplet
i	spatial index
inj	injection
l	species index
m	fluid medium
n	temporal index
osc	oscillatory
p	particle
qs	quasisteady
t	transient

GOAL:

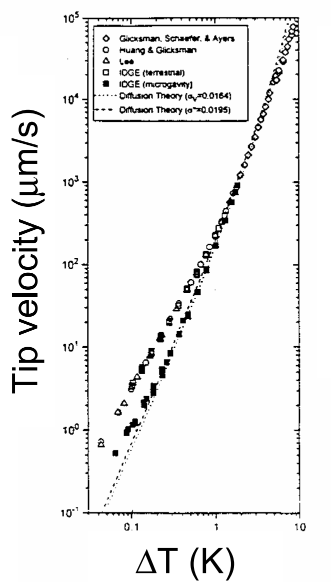
Predict sensitivity of the experiment to the acceleration environment

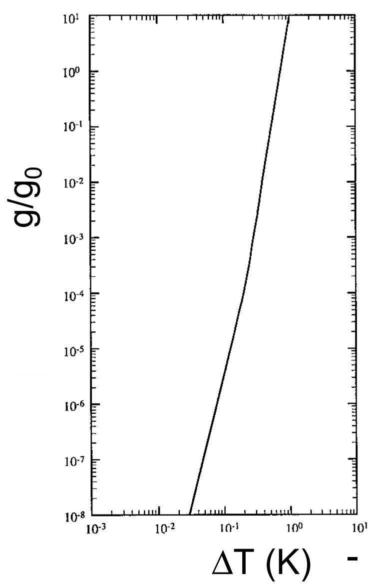
- PI must justify ***need for microgravity***
- PI must be able to predict ***tolerable*** (and intolerable) ***environments***
- PI must be able to ***account for and/or control*** "indirect" effects of gravity

Equiaxed Dendritic Solidification Experiment (EDSE)



Tetrahedron Arrangement of Dendrites





- Sensitivity to g provided by Lee et al. (1996)

- Beckermann et al. (1998)

Microgravity justification: Bulk convection has significant impact on dendritic growth on earth at an undercooling ΔT<1.5K. At this ΔT, morphological details are very fine (<1μm); tip speed is high; and interactions are limited to distances of < 200 μm. Related experiment was able to obtain diffusion-controlled growth on the Shuttle for ΔT=0.2-1K, which provided grounds for optimism.

Microgravity requirements:

duration: 30-1000s

quasisteady: 30,000 μg for ΔT=0.3K; 760 μg for ΔT =0.2K; 2.3 μg for ΔT =0.1K

oscillatory: maximum 100 μg at *f*<0.5 Hz; maximum 1000 μg at *f*>0.5 Hz

Also, measure accelerations in vicinity of experiment with minimum bandwidth of 0-100 Hz with accuracy ±20%; time-tagged notification of accelerations outside specified levels

Strategy for assessing experiment sensitivity to the μg environment

(1) Identify the *tolerance criterion*

(2) *Correlate acceleration* to the tolerance criterion

(3) Examine *knowledge base* from previous experiments

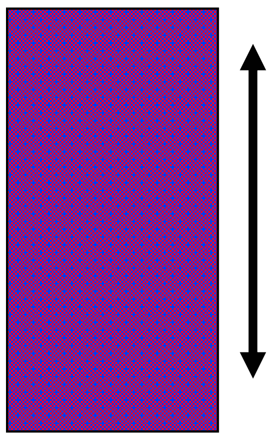
(4) Perform "simple" analyses to determine *range of sensitivity*

(5) Perform *detailed analysis* in the range of sensitivity and *examine specific microgravity environments*

(6) If possible, *test hypotheses* with prototypes on ground-based microgravity facilities, e.g., KC-135, drop tower

(7) Develop *detailed μg tolerance specifications*

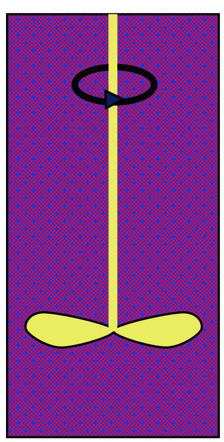
A note on mixing and filling in μg



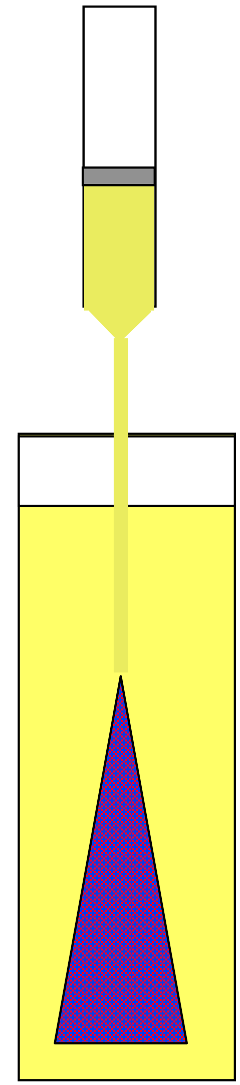
Shaking

<u>Goal:</u> Achieve a homogeneous distribution of additive in a fluid medium

- ***Stirring*** is most efficient (but increases hardware complexity)
- ***Shaking*** can improve homogeneity for multiphase flows (in general, better with ***increasing acceleration***, ***decreasing frequency***)
- ***Fluid motion through chamber*** can affect uniformity
- ***Massaging*** flexible-walled chamber mixes interior, but may add large ***unquantified forces*** on chamber contents
- ***Injection technique*** and ***design of chamber*** affects uniformity



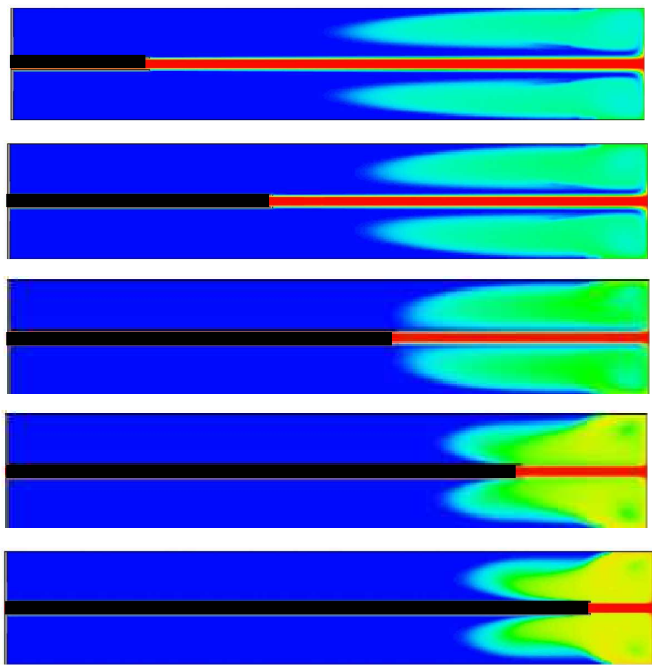
Stirring



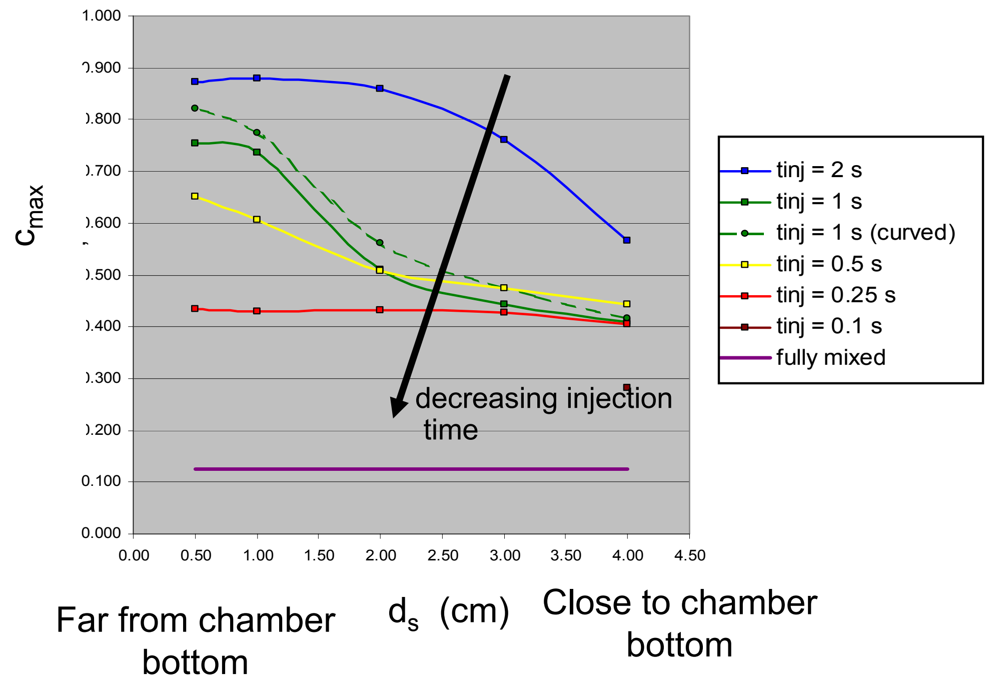
Injection

A note on mixing and filling (cont'd)

Effect of tip location on concentration field at t=10 sec



Effect of tip location and injection time on mixing

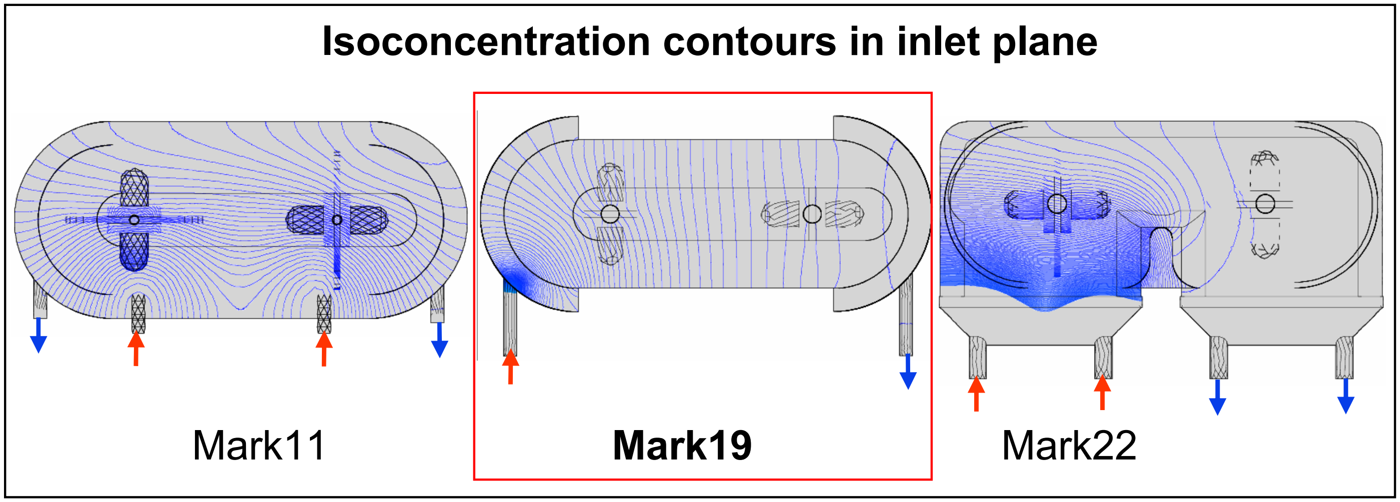


- Nelson and Juergensmeyer (2002)

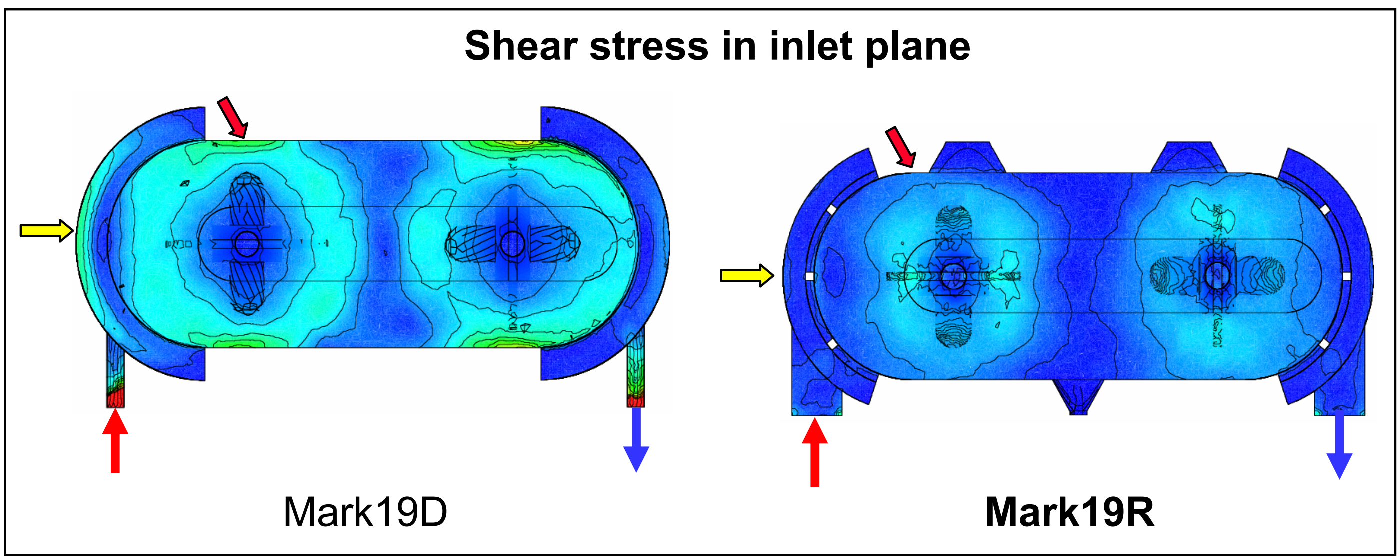
- ***Don't take mixing for granted***, particularly in microgravity
- Verify that the mixing itself ***does not place undesirable forces*** on the system

BTW, biologists and engineers/physicists should get along

Downselect Review



Interim Design Review



Case in point: Cell Specimen Chamber (CSC)

- CFD was crucial in identifying the best of 3 designs for providing the best conditions for homogeneity in the CSC
- CFD recommendations prompted tweaking of this design to increase inlet area and therefore velocities and shear rates in the CSC, as well as to to extend membrane height to minimize “bathtub” effect

- Nelson and Kizito (2002)

Choice of tolerance criteria

Tolerance criteria are:

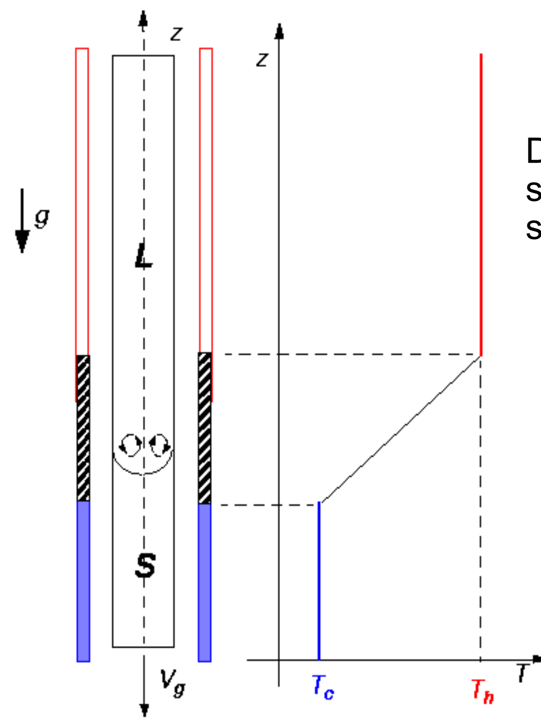
- ***subjective***; may be to some extent ***arbitrary***
- functions of ***many parameters***
  - fundamental physics
  - experiment goal
  - composition of system (thermophysical properties, etc.)
  - geometry of system (aspect ratio, length of test section, etc.)
  - applied boundary conditions (applied thermal or pressure field, velocity of boundaries, etc.)
  - etc.

A good tolerance criterion is evaluated in light of the ***specific experiment design*** and the ***specific environment*** in which it is placed

Examples of tolerance criteria

Ask the question: what does my experiment require to be a success?

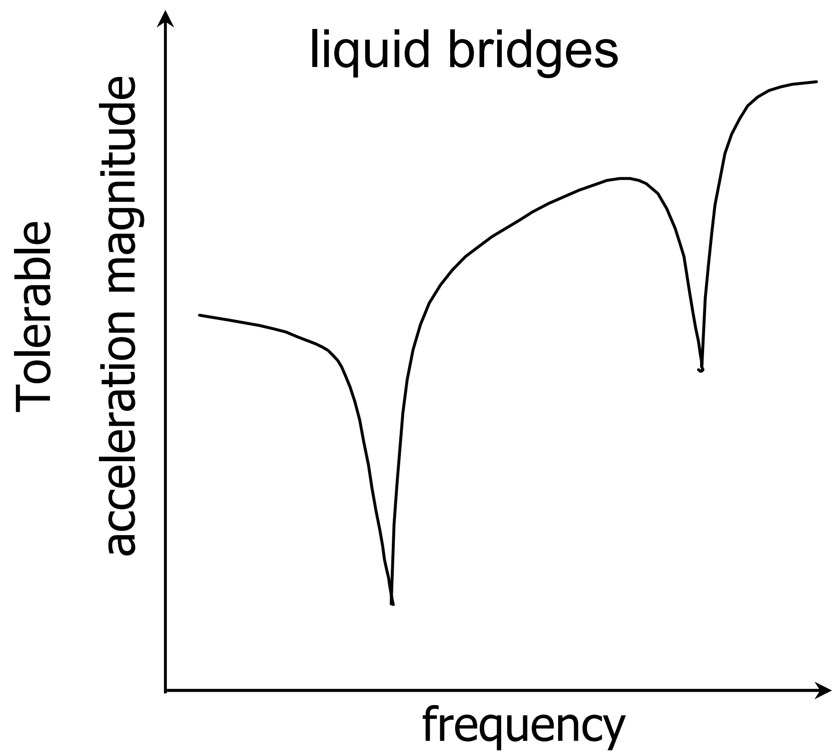
- fuel tank must not blow up
- no convective motion
- bubble/particle/droplet/gas can not hit chamber wall
- bubble can not tolerate distortion due to g
- interface shape must minimize curvature (as in melt solidification)
- μg environment must not change interface radial segregation (or granular temperature gradient or tip velocity or diffusive nutrient field or sphericity…) by more than 5% (1%, 10%, …)

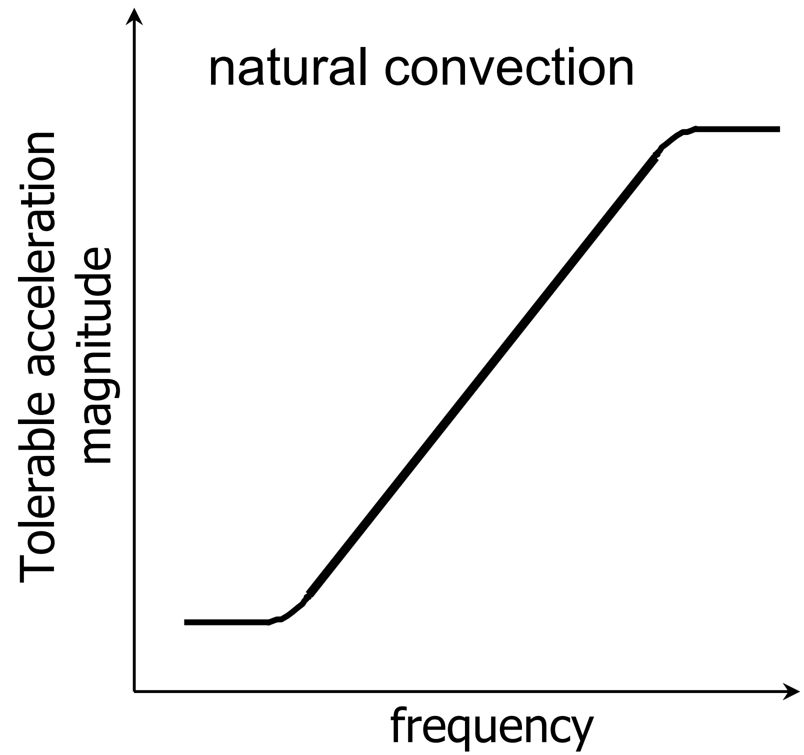


Directional solidification of semiconductor melt

Tolerance criterion: **5% variation in solute concentration** at solid/liquid interface (for example)

Correlate acceleration to tolerance criterion





Are there any broad statements that can be made?

- Is this experiment likely to
  - have ***resonance phenomena***?
  - have a ***ceiling*** or ***floor*** to the μg tolerance
  - show typical fluid response of ***increasing tolerance with increasing frequency***?

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

Correlating acceleration to tolerance criterion (cont'd)

- Examine ***acceleration field***:
  - terrestrial 1g, μg on a particular carrier, centrifuge, clinostat, etc.
  - acceleration ***magnitude***, ***frequency***, ***orientation***, and ***duration***

- Examine the ***system response*** to acceleration
  - compare ***time scales, length scales*** and ***forces*** in the experiment
  - if relevant, estimate experiment sensitivity to ***specific*** frequencies, orientations
  - if relevant, estimate sensitivity ***floor*** and/or ***ceiling*** on frequency or magnitude of acceleration
  - may require examination of ***overall*** momentum input
  - may need ***long recovery*** *times* for short disturbances, especially for flows in which diffusion of momentum is large in comparison to the diffusion of the desired quantity (e.g., Schmidt or Prandtl number)

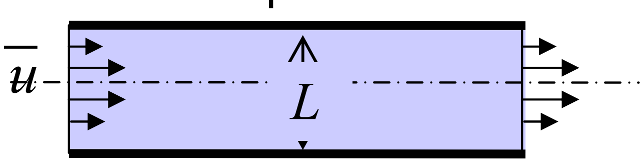
Determine range of sensitivity

- There will probably be ***many*** relevant characteristic time and velocity ***scales*** in a problem
- Maximum time scale can put a ***lower bound*** on frequency (f=1/period)
- Minimum time scale may put an ***upper bound*** on frequency

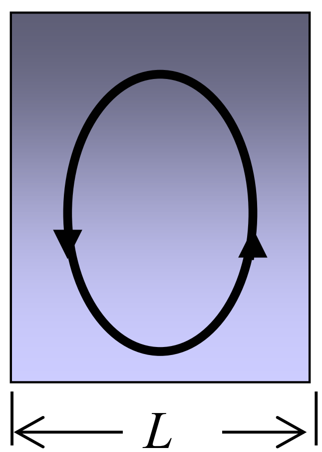
Examples of time scales

- ***Duration of experiment***
- Estimate ***characteristic time scales***:
  - diffusive, $t = L^2/D$
  - convective, $t = L/U$
  - reactive, …

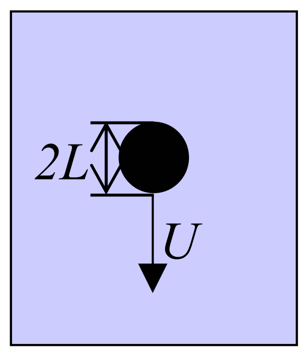
Pipe flow



Natural convection

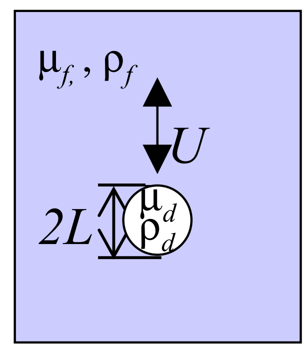


Particles



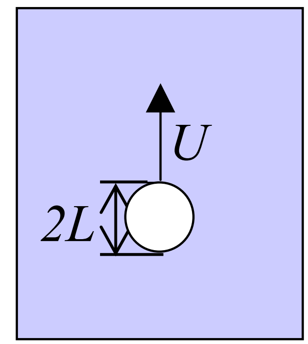
$U_t \sim 2gL^2/9\nu$

Droplets



$$U_t \sim \frac{2gL^2(\rho_d - \rho_f)(\mu_f + \mu_d)}{3\mu_f(2\mu_f + 3\mu_d)}$$

Bubbles



$U_t \sim gL^2/3\nu$

Examine relevant nondimensional numbers

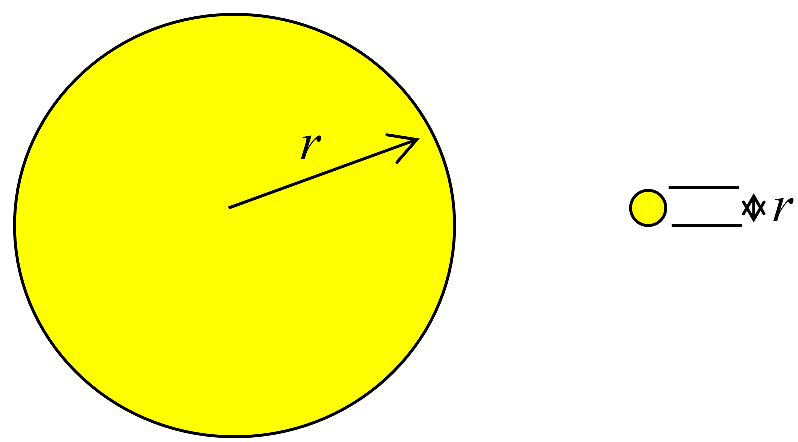
• Even for a non-fluids person, it may be possible to get a handle on sensitivity by computing particular nondimensional quantities from scaling analysis:

Nondimensional number	Typical scaling	Meaning
Bo = Bond number	$Bo = \frac{\rho g L^2}{\sigma}$	gravitational/surface tension
Ca = Capillary number	$Ca = \frac{\mu U}{\sigma}$	viscous/surface tension
Fr = Froude number	$Fr = \sqrt{\frac{U^2}{gL}}$	inertial/gravitational
Gr = Grashof number	$Gr = \frac{\beta_T \Delta T g L^3}{\nu^2}$	momentum diffusion (from natural convection) / viscous
Ma = Marangoni number	$Ma = \frac{\lvert\sigma_T \Delta T\rvert}{\mu U}$	diffusive/thermocapillary
Pr = Prandtl number	$\mathrm{Pr} = \frac{\nu}{\alpha} = \frac{\mu c_p}{k}$	momentum/thermal
Ra = Rayleigh number	$Ra = \frac{g \beta \Delta T L^3}{\nu \alpha} = Gr\,\mathrm{Pr}$	natural/forced convection
Re = Reynolds number	$\mathrm{Re} = \frac{\rho U L}{\mu}$	inertial/diffusive
Sc = Schmidt number	$Sc = \frac{\nu}{D} = \frac{\mu}{\rho \alpha_c}$	momentum/species diffusion
We = Weber number	$We = \frac{\rho L U^2}{2\sigma}$	inertial/surface tension

Estimation of forces

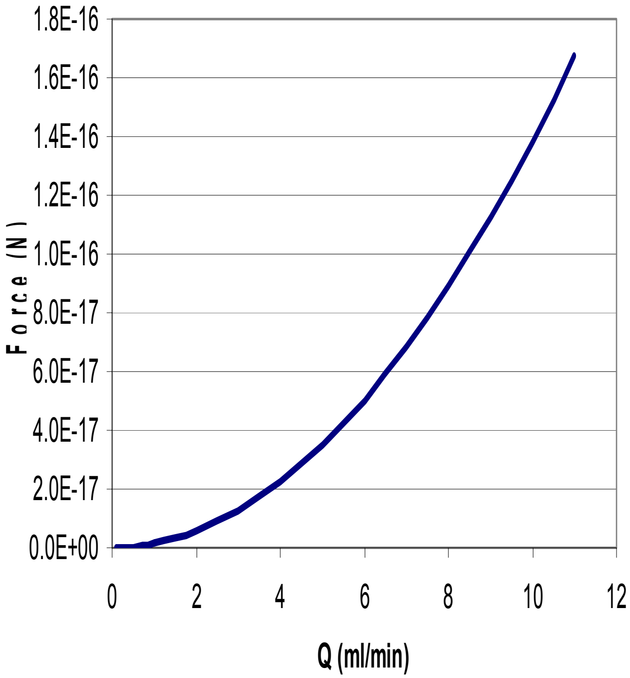
- Estimate all forces acting in the problem. For a small particle/bubble in liquid:
  - volumetric forces: weight, buoyancy, mixing(?), stirring(?), centrifugal, inertial, electrokinetic, electromagnetic
  - surface forces: friction, drag, surface tension, thermocapillary, etc.
- Rank forces
- Are any gravity-related forces on the order of or larger than the other forces?
- In general, as size decreases, the importance of gravitational forces relative to surface forces decreases. For a sphere, the surface-to-volume ratio, S/V, is:

$$\frac{S}{V} = \frac{4\pi r^2}{\frac{4}{3}\pi r^3} = \frac{3}{r}$$

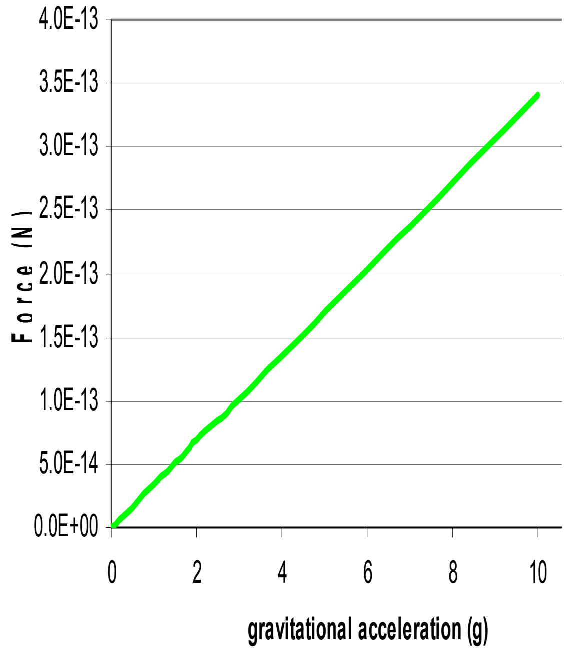


Estimate forces over the range of operating parameters

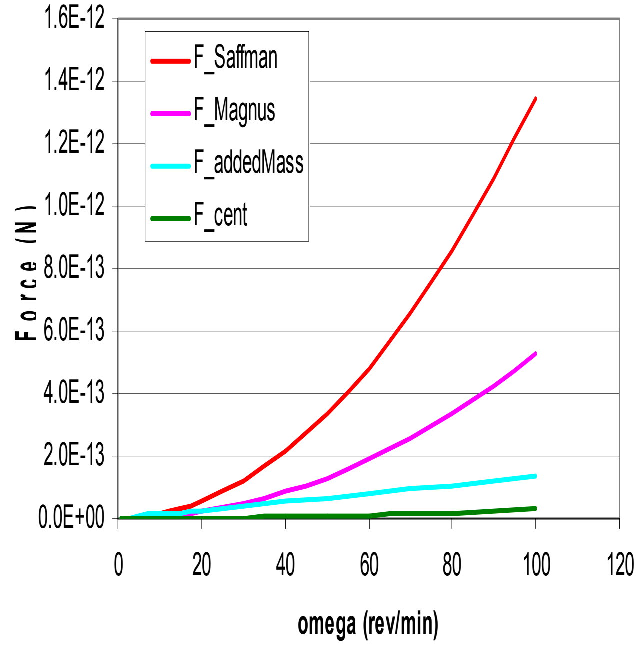
<u>Example</u>: forces in a cell specimen chamber acting in the fluid and on a yeast cell



Force due to incoming jet

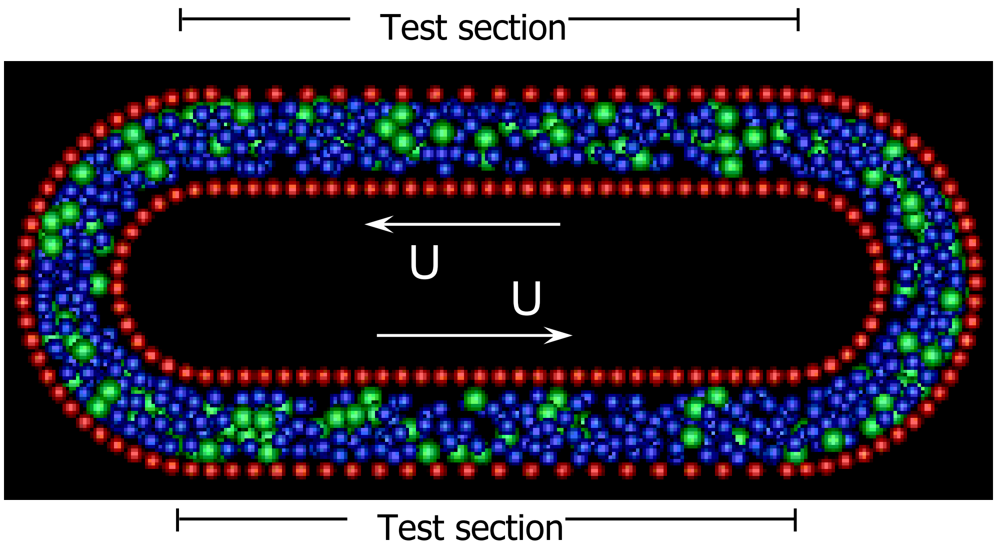


Force due to sedimentation



Saffman, Magnus, added mass, and centrifugal forces

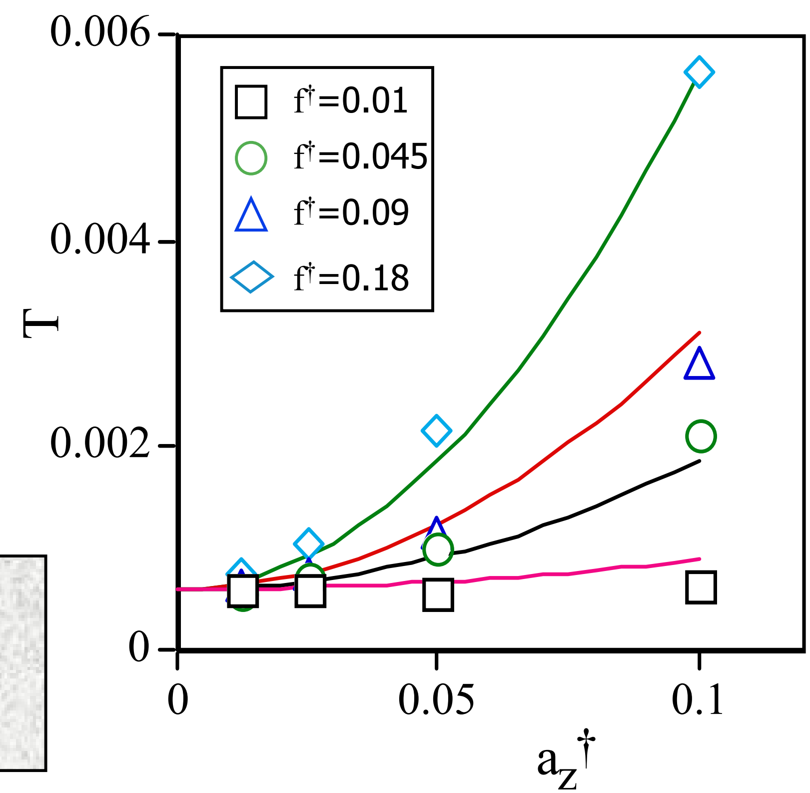
Perform detailed analysis in range of sensitivity



<u>Tolerance criterion</u>: g-jitter can contribute up to **5% variation in mean granular temperature, T,** across test section

$$T = \frac{1}{3}\tilde{u}_i' \cdot \tilde{u}_i'$$

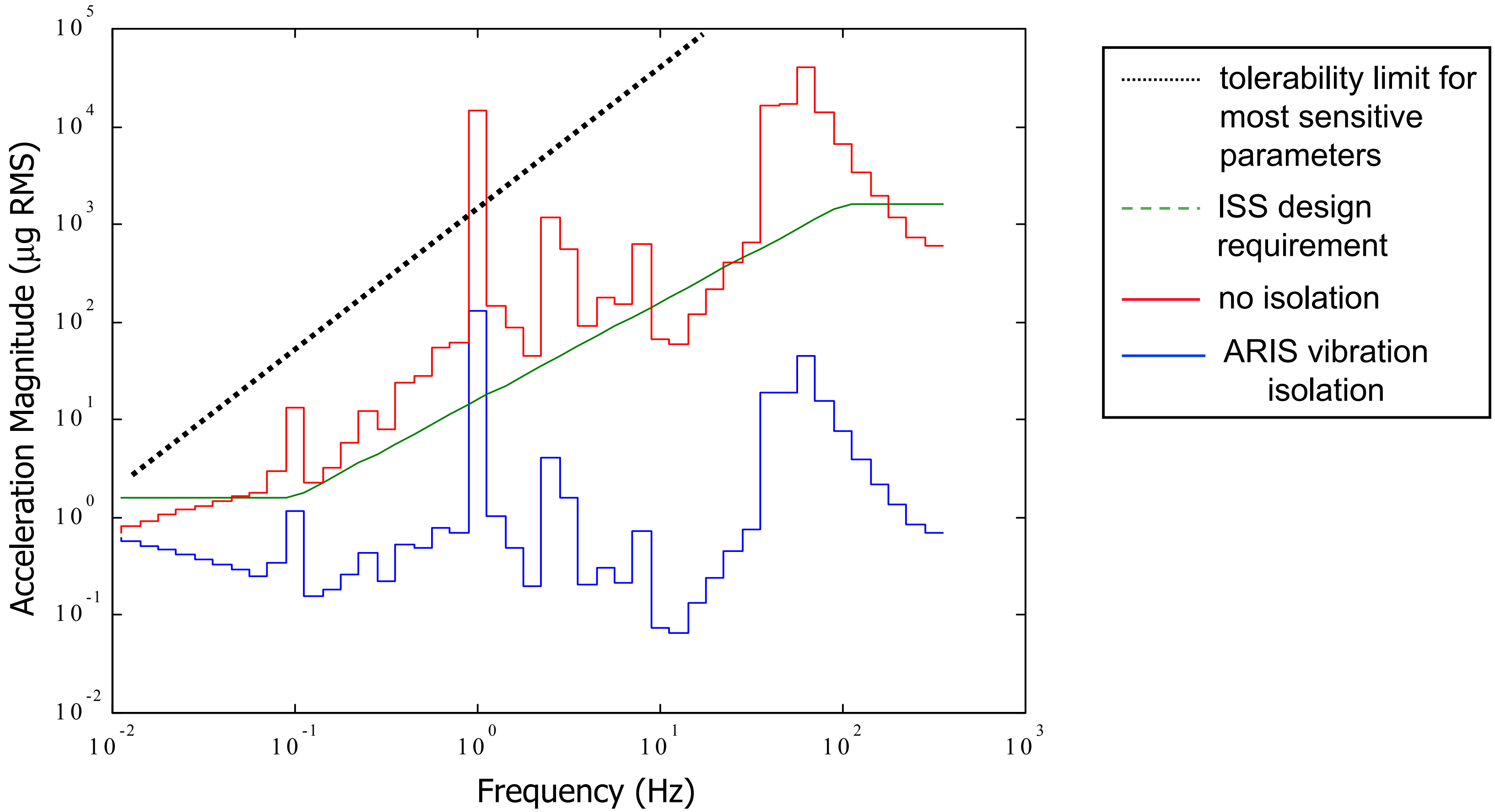
Microgravity segregation of energetic grains (μgseg)



$$T = T_0 + c_i\, f^\dagger a^{\dagger 2}$$

- Jenkins and Louge (1998)

Tolerability limits for μgSEG



- Jenkins and Louge (1998)

Examine knowledge base

Browse through the microgravity sites to find experiments with similar physics:

- Fluid physics, materials science, combustion: **http://microgravity.grc.nasa.gov/new/expermnt.htm**
- Life sciences: **http://gateway.nlm.nih.gov**, **http://lsda.jsc.nasa.gov**
- ESA microgravity database: **http://www.esa.int/cgi-bin/mgdb**
- Microgravity Research Experiments database (MICREX): **http://mgravity.itsc.uah.edu/microgravity/micrex/micrex.stm**
- NASA Technical Reports Server: **http://techreports.larc.nasa.gov/cgi-bin/NTRS**

Note: for a good science dictionary, see **http://www.onelook.comhttp**

Developing detailed microgravity tolerance specifications

- **Describe the *quasisteady* acceleration limits**
  - upper bound of QS ***magnitude*** (expect several μg on ISS)
  - desired ***orientation*** (if choices are available)
  - angular ***tolerance*** about that orientation (e.g., align experiment with torque equilibrium attitude (TEA) of ISS with a tolerance of ± 0.05°. Maintain $\mathbf{g}_{qs}$ orientation to within TEA ± 10°)

- **Identify *oscillatory* acceleration limits**
  - ***specific frequencies*** at particular magnitudes of concern
  - frequency ***cutoffs*** (examine both upper and lower bounds)

- **Describe *transient* acceleration limits**
  - ***thumbs up/down for identified transients*** (based on thruster firings, impulsive crew activity, etc., e.g., 100 μg for up to 2 sec);
  - specify ***integrated acceleration input*** subject to limits (e.g., 300 μg-sec with magnitude ≤ 150 μg)

Developing detailed μg tolerance specifications (cont'd)

- **Specify *duration* of experimental runs**
  - ***typical*** length
  - anticipated ***maximum/minimum*** length
  - expected ***number of runs*** per 30-day microgravity period
- **Give *thumbs up/down for specific environments*, e.g.,**
  - Shuttle, sounding rocket, free flyer, KC-135, ISS
  - examine possibilities for vibration isolation
    - isolated vs. unisolated rack
    - ARIS vibration isolation
    - passive vibration isolation
    - MIM, g-LIMIT, or other active sub-rack isolation unit

and ***specific disturbances***

- question experiments that are likely to interfere if run simultaneously (see DeLombard et al., 1998, for an example)

Recap: Strategy for assessing experiment sensitivity to the μg environment

(1) Identify the *tolerance criterion*
(2) *Correlate acceleration* to the tolerance criterion
(3) Examine *knowledge base* from previous experiments
(4) Perform "simple" analyses to determine *range of sensitivity*
(5) Perform *detailed analysis* in the range of sensitivity and *examine specific microgravity environments*
(6) If necessary and possible, *test hypotheses* with prototypes on ground-based microgravity facilities, e.g., KC-135, drop tower
(7) Develop *detailed μg tolerance specifications*

Bibliography

Abbaschian, R. *"Bismuth-tin crystal growth."* Science Requirements Document (March, 1993).

Beckermann, C., H.C. de Groh III, I. Steinbach and A. Karma. *"Equiaxed dendritic solidification experiment (EDSE)."* Science Requirements Document (February, 1998).

Berg, R.F. and M.R. Moldover. *"Critical viscosity experiment."* Science Requirements Document (199?).

Chaikin, P.M., W.B. Russel, and J.S. Ling. *"Physics of hard spheres experiment (PHASE)."* Science Requirements Document (1994?).

Colwell, J.E. *"Collisions into dust experiment - 2"* Science Requirements Document (January, 1999).

De Groh, H.C. and E.S. Nelson. "*On residual acceleration during space experiments*." **ASME HTD-Vol 290**, pp 23-33 (1994).

DeLombard, R.K., K. Hrovat, and K. McPherson. *"Experiment-to-experiment disturbance of microgravity environment."* **AIAA-99-0576** (Also NASA TM-1998-208847) (1998).

Demel, K. "*Implications of acceleration environments on scaling materials processing in space to production*." In Measurement and characterization of the acceleration environment on board the Space Station. NASA/MSFC and Teledyne Brown. Aug 11-14 (1986).

Dodge, F.T. *"Liquid motion in a rotating tank experiment (LME)."* Science Requirements Document (August, 1994).

Fernandez-Pello, C. *"Smoldering combustion experiment in microgravity."* Science Requirements Document (November, 1992).

Feuerbacher, B., H. Hamacher and R. Jilg. *"Compatibility of microgravity experiments with spacecraft disturbances."* **Z Flugwiss Weltraumforsch 12:**145-151 (1988).

Bibliography (cont'd)

Louge, M. and Jenkins, J. *"Studies of gas/particle interactions in a microgravity flow cell."* Science Requirements Document (May, 2000).

Jenkins, J. and M. Louge. "*Microgravity Segregation of Energetic Grains*." Science Requirements Document (1998).

Matthiesen, D.H. *"Diffusion processes in molten semiconductors."* Science Requirements Document (June, 1996).

McKinley, G.H. *"The extensional rheology experiment."* Science Requirements Document (February, 1997).

Ronney, P.D. *"Structure of flame balls at low Lewis number (SOFBALL)."* Science Requirements Document (October, 1994).

T'ien, J.S. and K.R. Sacksteder. *"Solid inflammability boundary at low speed (SIBAL)."* Science Requirements Document (1995).

Voorhees, P.W. *"Coarsening in solid-liquid mixtures."* Science Requirements Document (June, 1994).

Weitz, D.A. and P.N. Pusey. *"Physics of colloids in space."* Science Requirements Document (July, 1997).