An Improved Model of Cryogenic Propellant Stratification in a Rotating, Reduced Gravity Environment

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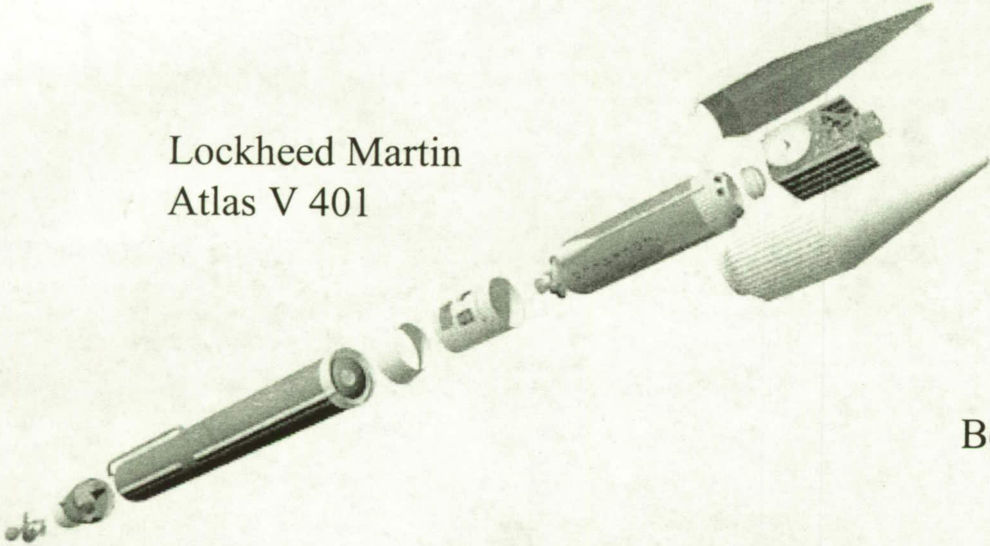
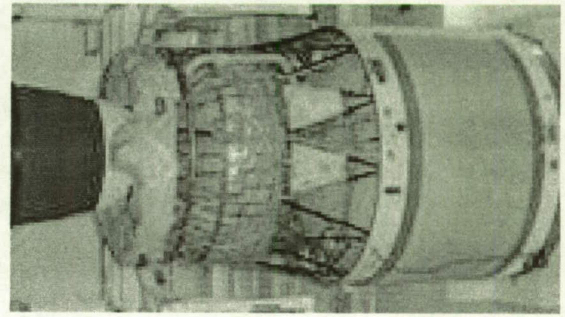
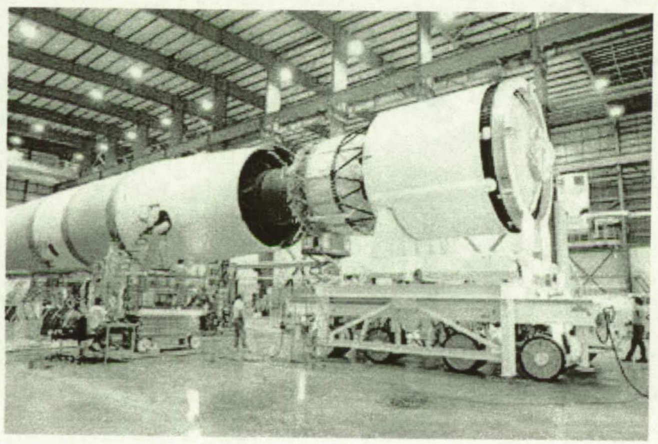
OVERVIEW: UPPER STAGE MODELING

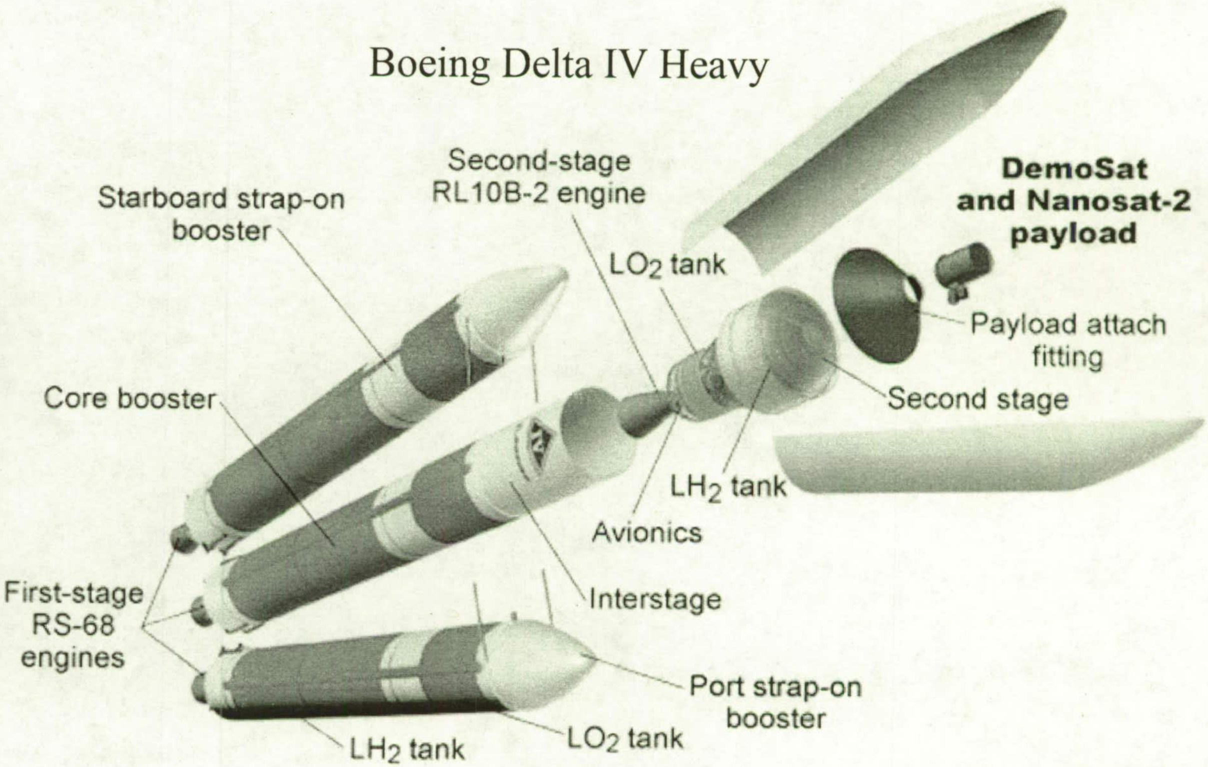
Lockheed Martin
Atlas V 401





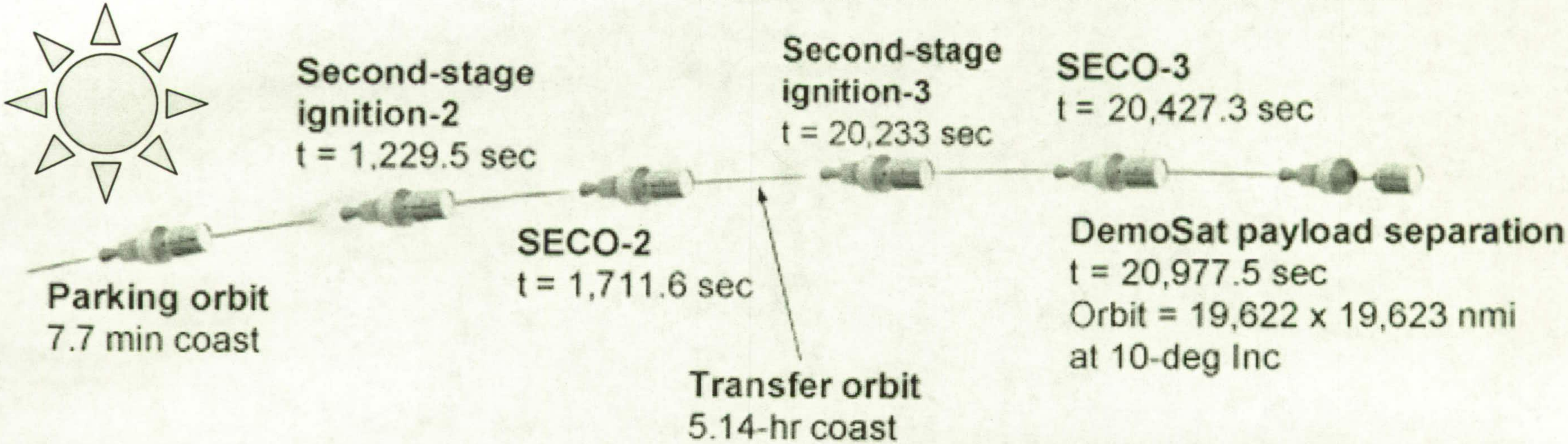
Boeing Delta IV Heavy



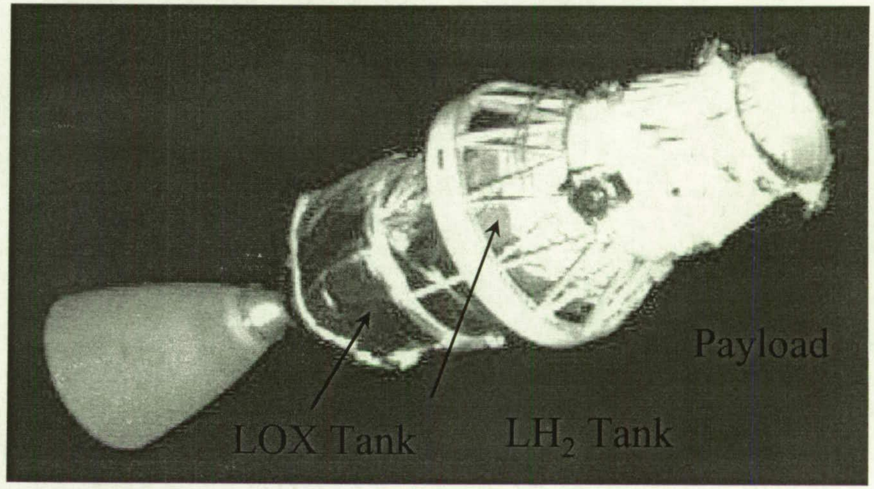


http://www.boeing.com/defense-space/space/delta/delta4/d4h_demo/book04.html

OVERVIEW: WHAT CAN HAPPEN INSIDE TANKS?



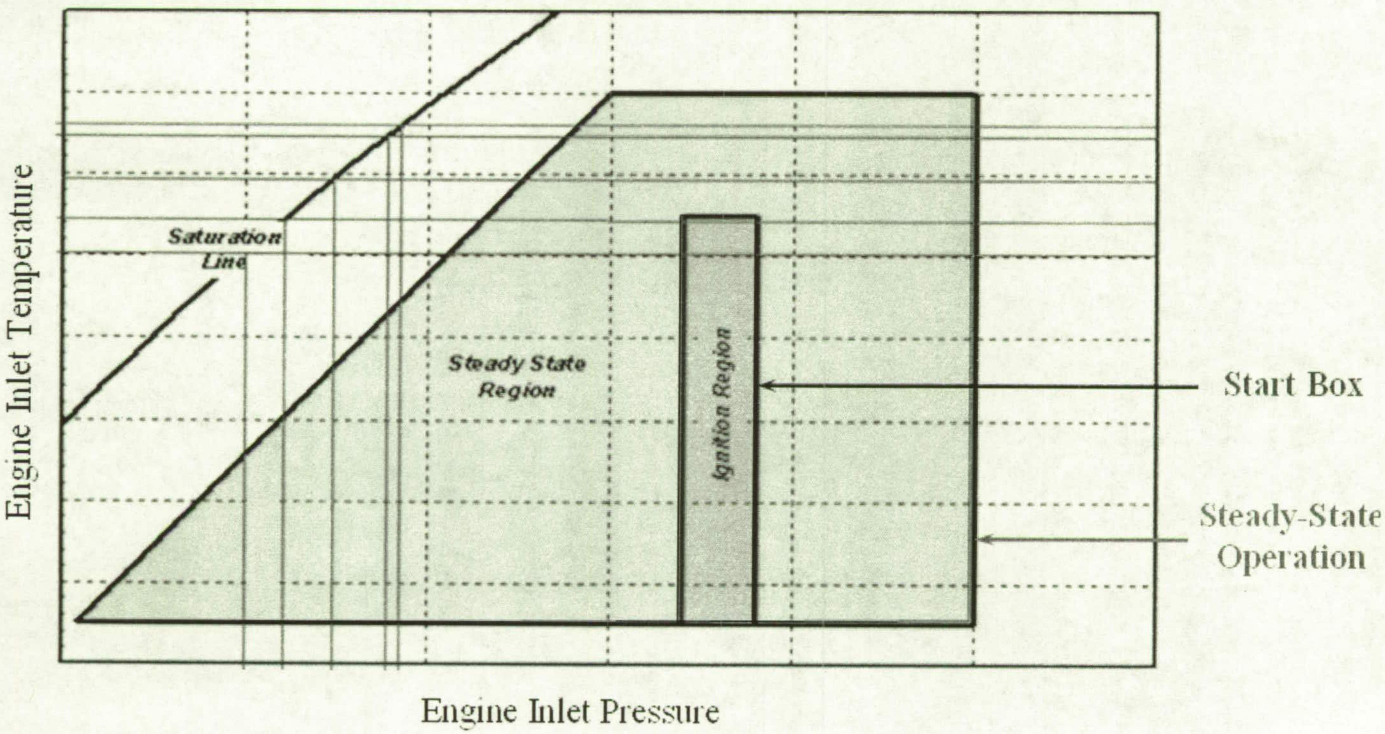
- Stage exposed to solar heating
- Propellants (LH_2 and LOX) may thermally stratify
- Propellants may boil
- Slosh events during maneuvers
- Upper stage must re-start at conclusion of coast phase for insertion

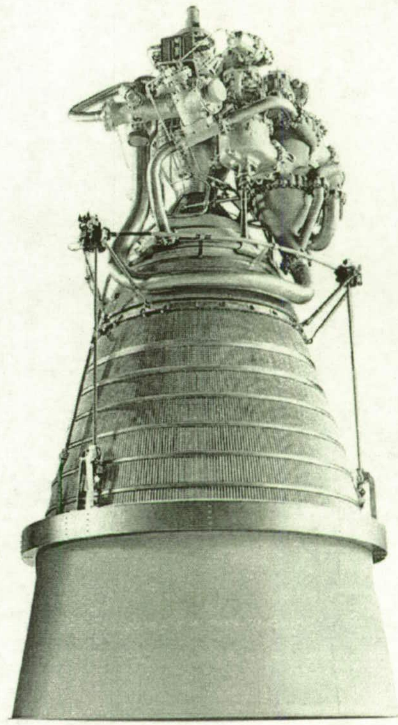


http://www.boeing.com/defense-space/space/delta/delta4/d4h_demo/book14.html
XSS-10 view of Delta II rocket: An Air Force Research Laboratory XSS-10 micro-satellite uses its onboard camera system to view the second stage of the Boeing Delta II rocket during mission operations Jan. 30. (Photo courtesy of Boeing.), http://www.globalsecurity.org/space/systems/xss.htm

OVERVIEW: WHAT CAN HAPPEN INSIDE TANKS?

- Propellant T&P must be within specified range for turbomachinery operation
  - If propellants outside specified T&P box engine may not restart
  - Orbit cannot be circularized

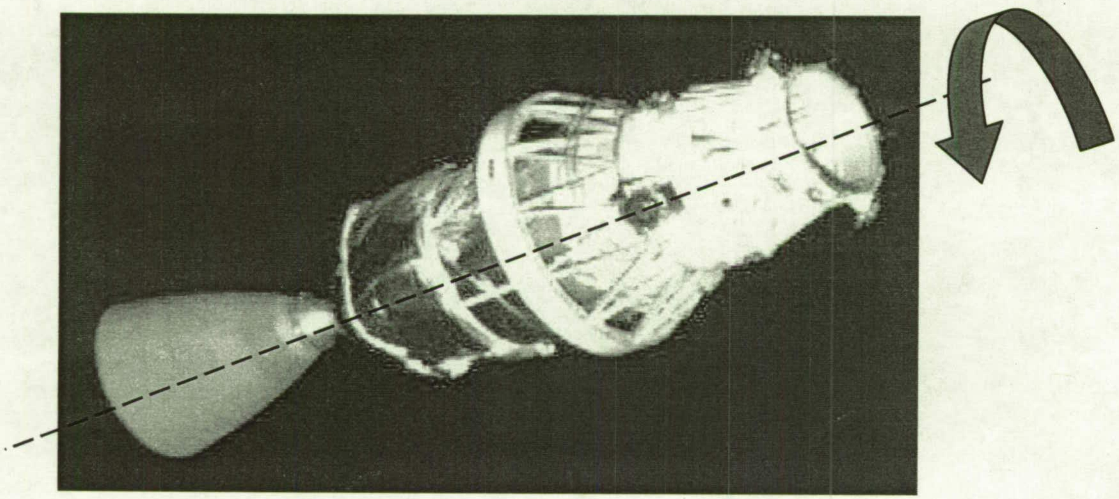


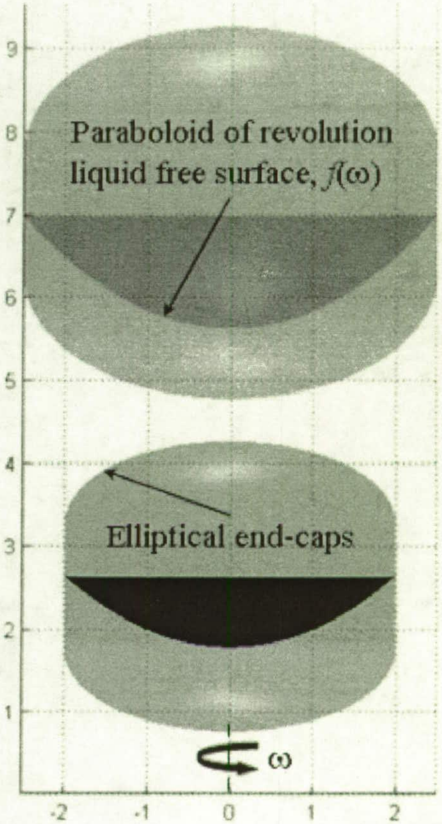


.pratt-whitney.com/prod_space_rl10.asp

MOTIVATION

- Rotation present during missions to evenly heat spacecraft
- Effect rotation has on propellant thermal properties unknown
- Upgrade current analytical/numerical stratification models to include rotation





MISSION PARAMETER RANGES

- Tank Dimensions:
  - Square 3 m diameter tanks
- Cryogenics: **LH_2, LOX**
  - T_{bulk} LH_2: 16 K, 28.8 °R, -430.9 °F
  - T_{bulk} LOX: 91 K, 163.8 °R, -295.9 °F
- Tank Pressure (All Cryogenics): 30 psi
- Initial Fill Levels: 10, 20, 30%

- Heating Conditions:
  - Constant wall temperature: $\theta = T_{wall} - T_{bulk}$: $\Delta T = 0.1, 0.5, 1.0$ K
  - Heat flux to fluid: 5-100 W/m^2

- Reduced Gravity Environment: $g/g_0 = 10^{-4}, 10^{-3}, 10^{-2}, 10^{-1}, 1$
- Rotation rates: $\omega = 0.1, 1, 5$ °/sec
- Orbital Transfer Time (Simulation Time): 2 – 4 HR

MASTER MODEL: BASIC FRONT END OPTIONS

1. Tank geometry
   - Tank diameter, height
   - Square bottom

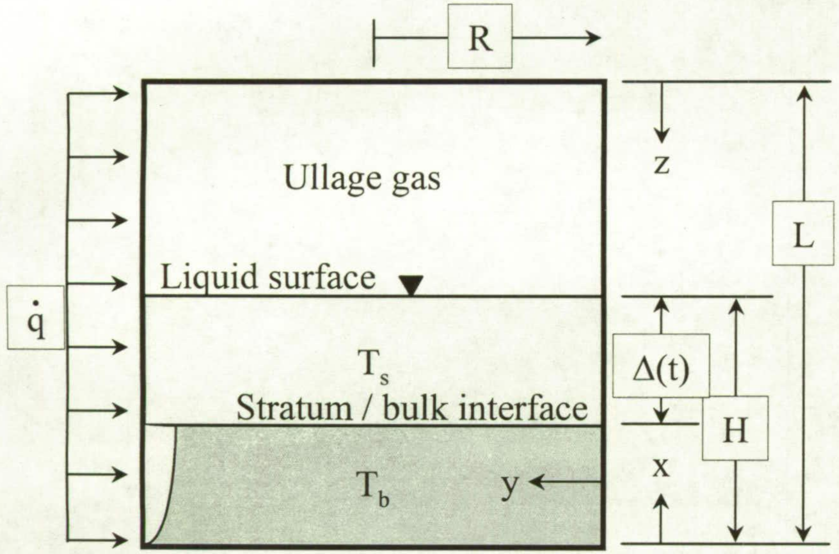
2. Boundary layer nature and heat transfer coefficient selection
   - Free convection
     - Laminar/Turbulent (w/ & w/out switching)

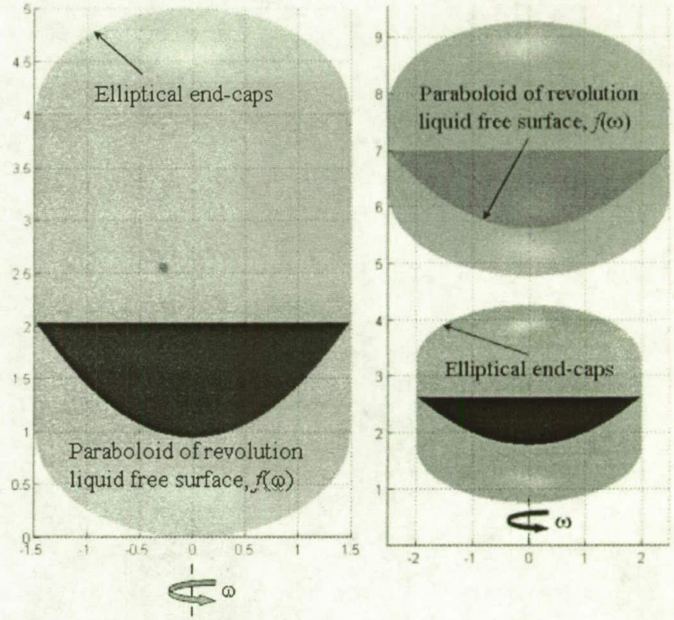
3. Wall temperature settings
   - Constant inner wall temperature
   - Constant inner wall heat flux

4. Rotation rate

5. Gravity level

GENERAL MODELING PHILOSOPHY





- Stratum growth $\Delta(t)$
  - u(y) depends on if heating is constant wall temperature or constant heat flux, q
  - u(y) depends on nature of boundary layer
  - Provides differential equation for $\Delta(t)$

$$\dot{m}_{bl} = 2\pi R\rho \int_0^{\delta} u(y)dy = \rho\pi R^2 \frac{d\Delta}{dt}$$

- Stratum temperature, $T_s(t)$
  - Heat entering side wall into boundary layer is used to increase stratum temperature
  - Energy exchange with ullage negligible
  - T_s assumed uniform

$$\dot{q}2\pi RH = \rho\pi R^2 \Delta c_p \frac{dT}{dt}$$

RELEVANT NON-DIMENSIONAL NUMBERS

$$Gr = \frac{g\beta\theta L^3}{\nu^2}$$

- Grashof number, **Gr**, governs heat transfer regime for constant wall temperature
  - Ratio of buoyancy to viscous forces
  - β, Volumetric thermal expansion coefficient
  - θ, Wall to Bulk temperature difference

$$Ra = Gr\,\mathrm{Pr}$$

- Rayleigh number, **Ra**, is product of Grashof and usual Prandtl number, **Pr**
- Prediction of boundary layer transition
  - If **Ra** $< 10^9 \rightarrow$ Laminar
  - If **Ra** $> 10^9 \rightarrow$ Turbulent

$$Gr^* = \frac{g\beta q_w L^4}{k\nu^2}$$

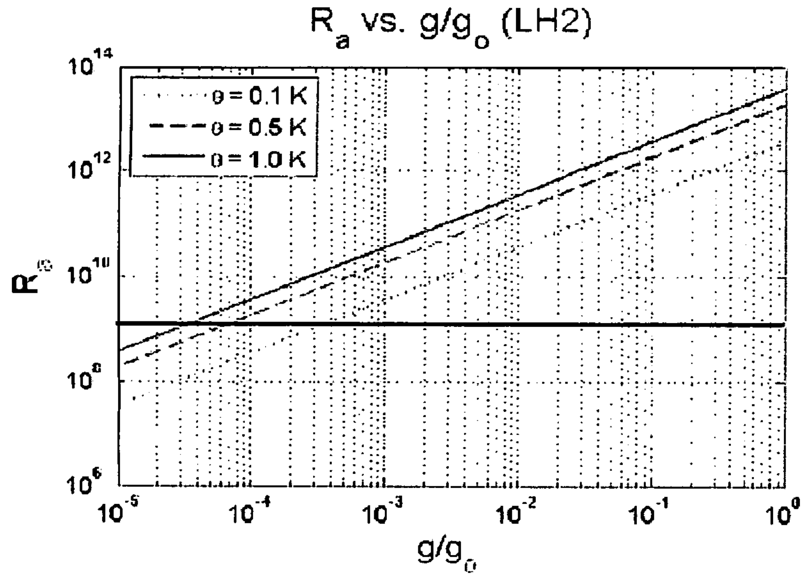
- Modified Grashoff number, **Gr***, governs heat transfer regime for uniform heat flux, q_w

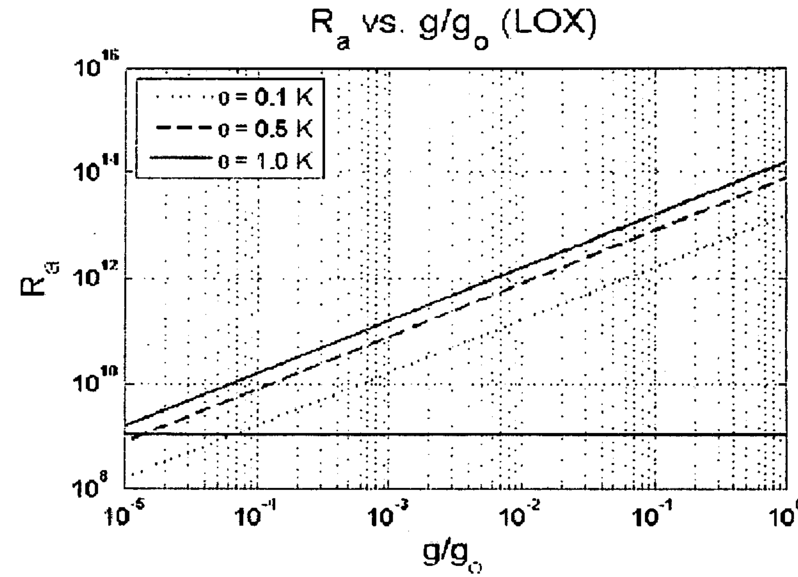
$$Ra^* = Gr^*\,\mathrm{Pr}$$

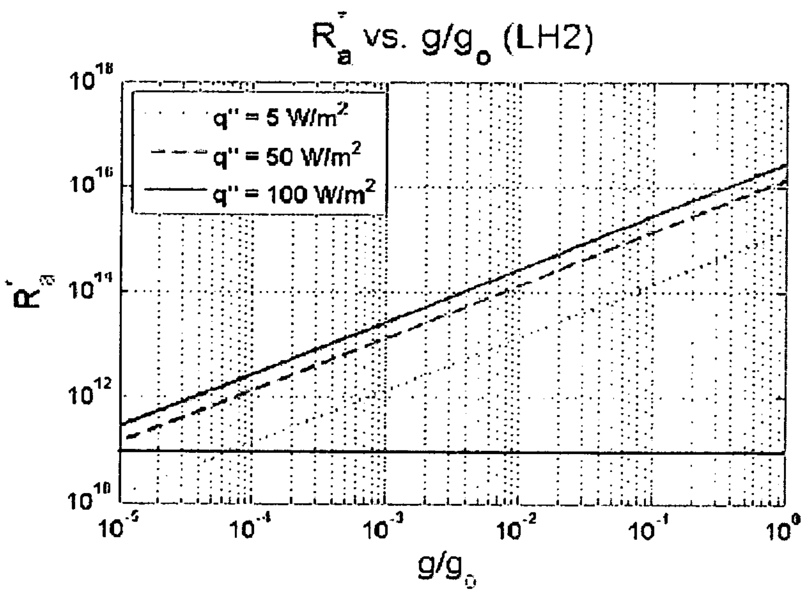
- Modified Rayleigh number, **Ra***, for uniform heat flux

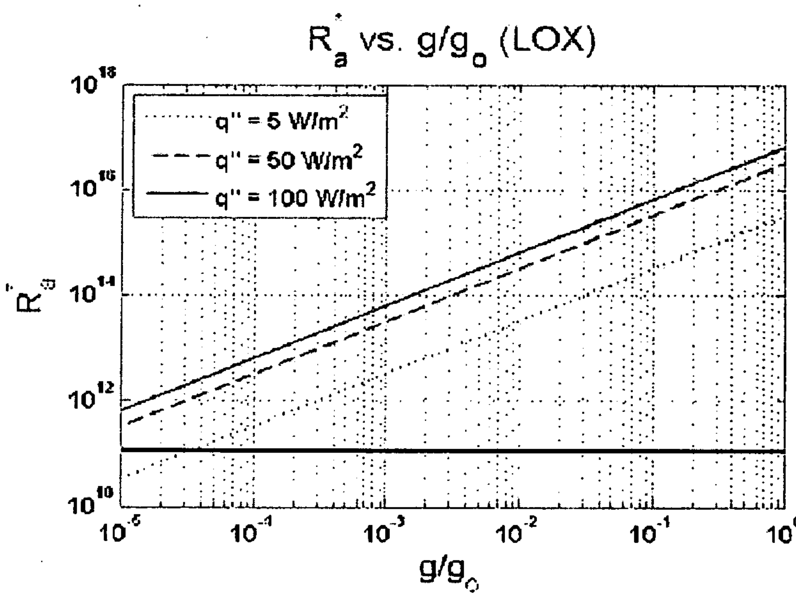
- Others: Reynolds Number, **Re** (momentum to viscous) Weber number, **We** (inertial to capillary), Froude number, **Fr** (inertial to body), and Bond number **Bo** (body to capillary)

Ra and Ra* vs. g/g_0 MAPS for LH_2 and LOX





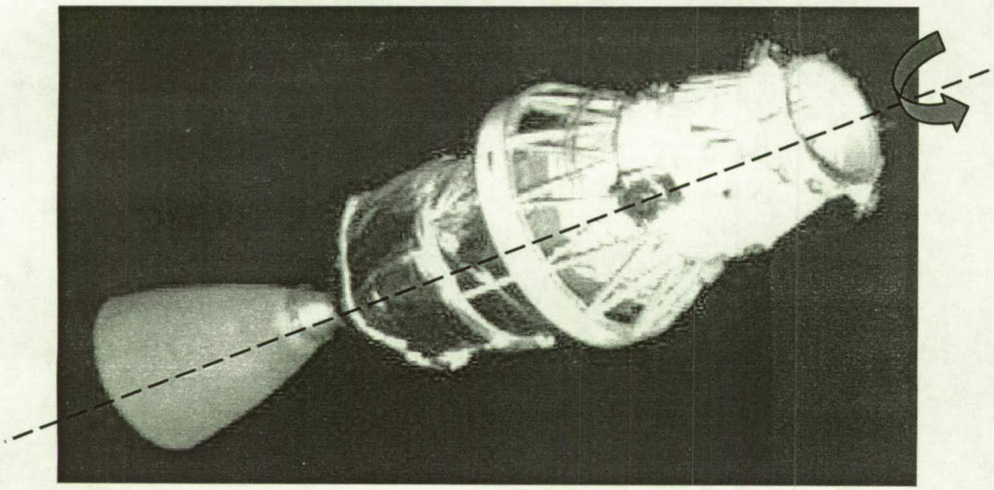




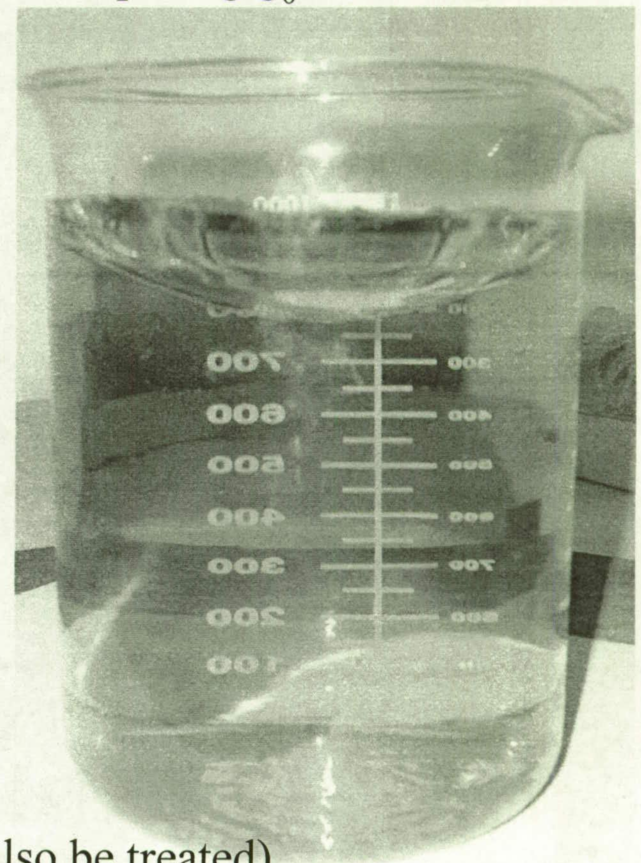
- Maps laminar or turbulent boundary layers possible for typical mission profiles (NIST data)

WHAT IS IMPACT OF BBQ ROLL ROTATION:

Typical rotation rate, $\omega \sim 1°/sec$



Shape at $g/g_0=1$, $\omega \sim 850°/sec$



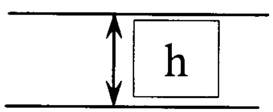
- Does 1°/sec matter?
- Not at $g/g_0=1$ but in coast phase $g/g_0 \sim 10^{-4}$
  → significant dishing effect

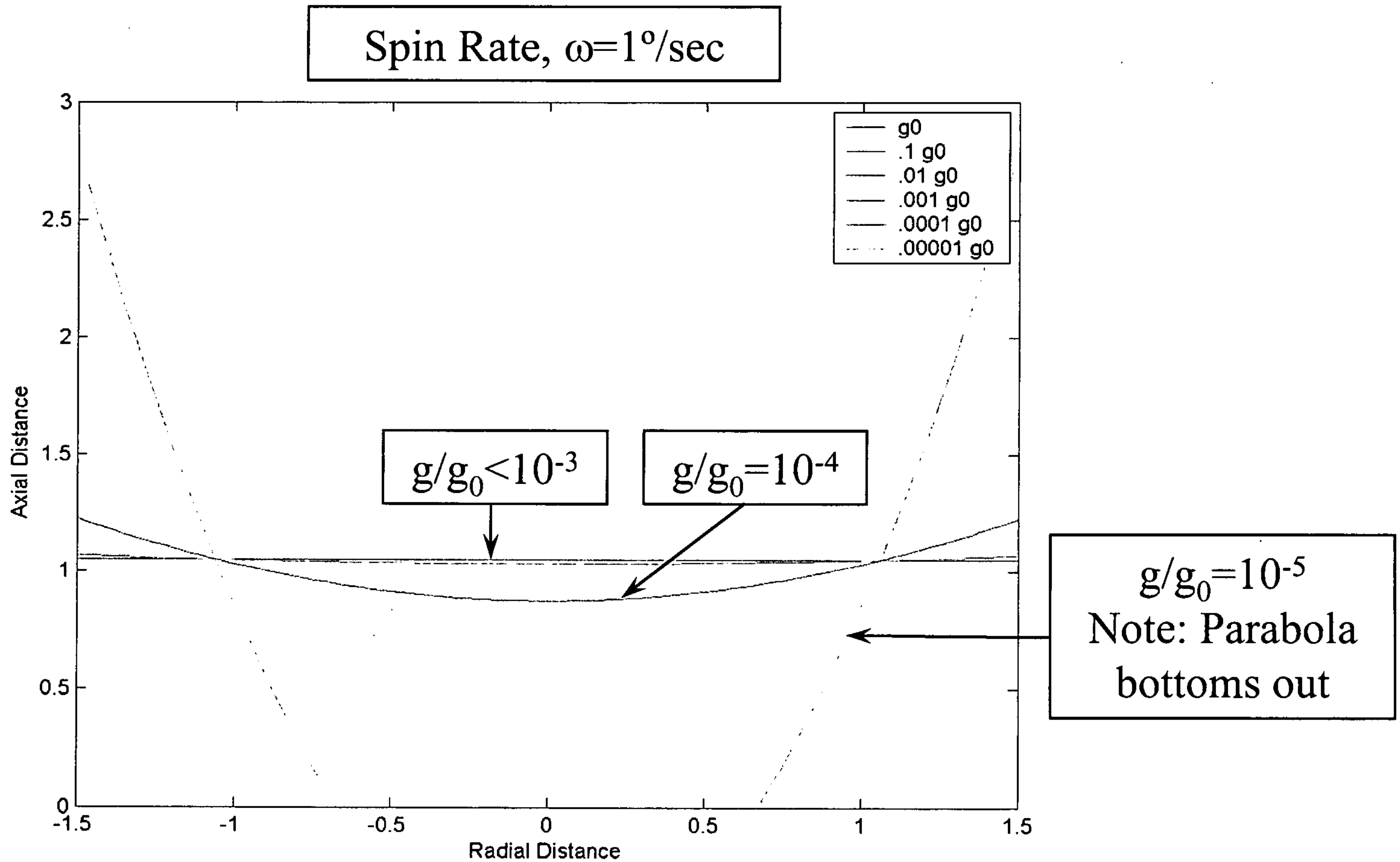
Key Question: How does rotation impact results?

- Assume liquid is in solid body rotation (transients can also be treated)
- Model extra height that liquid gains along wall as a longer interfacial heat transfer length
- Center point in radial direction of tank is taken to be point where percent of bulk remaining is referenced → worst case scenario
- Trade off between heated area and surface area to distribute warm stratum

ROTATION / STRATIFICATION COMBINED MODEL

$$h = \frac{(\omega R)^2}{2g}$$





ROTATIONAL CASES

Re-examine boundary layer / stratum mass balance

$$\dot{m}_{bl} = \pi R^2 \rho\left(\frac{d\Delta}{dt}\right) = S_{paraboloid}\,\rho\left(\frac{d\Delta}{dt}\right) = \frac{\pi R}{6h^2}\left[\left(R^2 + 4h^2\right)^{3/2} - R^3\right]\rho\left(\frac{d\Delta}{dt}\right)$$

Turbulent

$$\frac{\Delta(t)}{H_\omega} = 1 - \left[1 + 0.082\frac{H_\omega \pi R}{S_p}\left(Gr_\omega^*\right)^{2/7}\frac{1}{\Pr^{2/7}}\phi_\omega\right]^{-7}$$

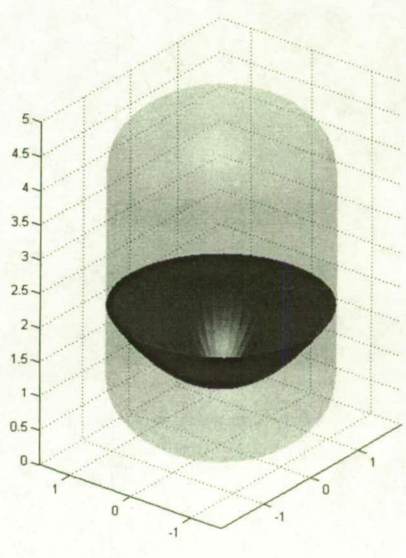
Laminar

$$\frac{\Delta(t)}{H_\omega} = 1 - \left[1 - 0.616\frac{H_\omega \pi R}{S_p}\frac{\left(Gr_\omega^*\right)^{1/5}}{\left(\frac{4}{5} + \Pr\right)^{1/5}}\frac{1}{\Pr^{3/5}}\phi_\omega\right]^{5}$$

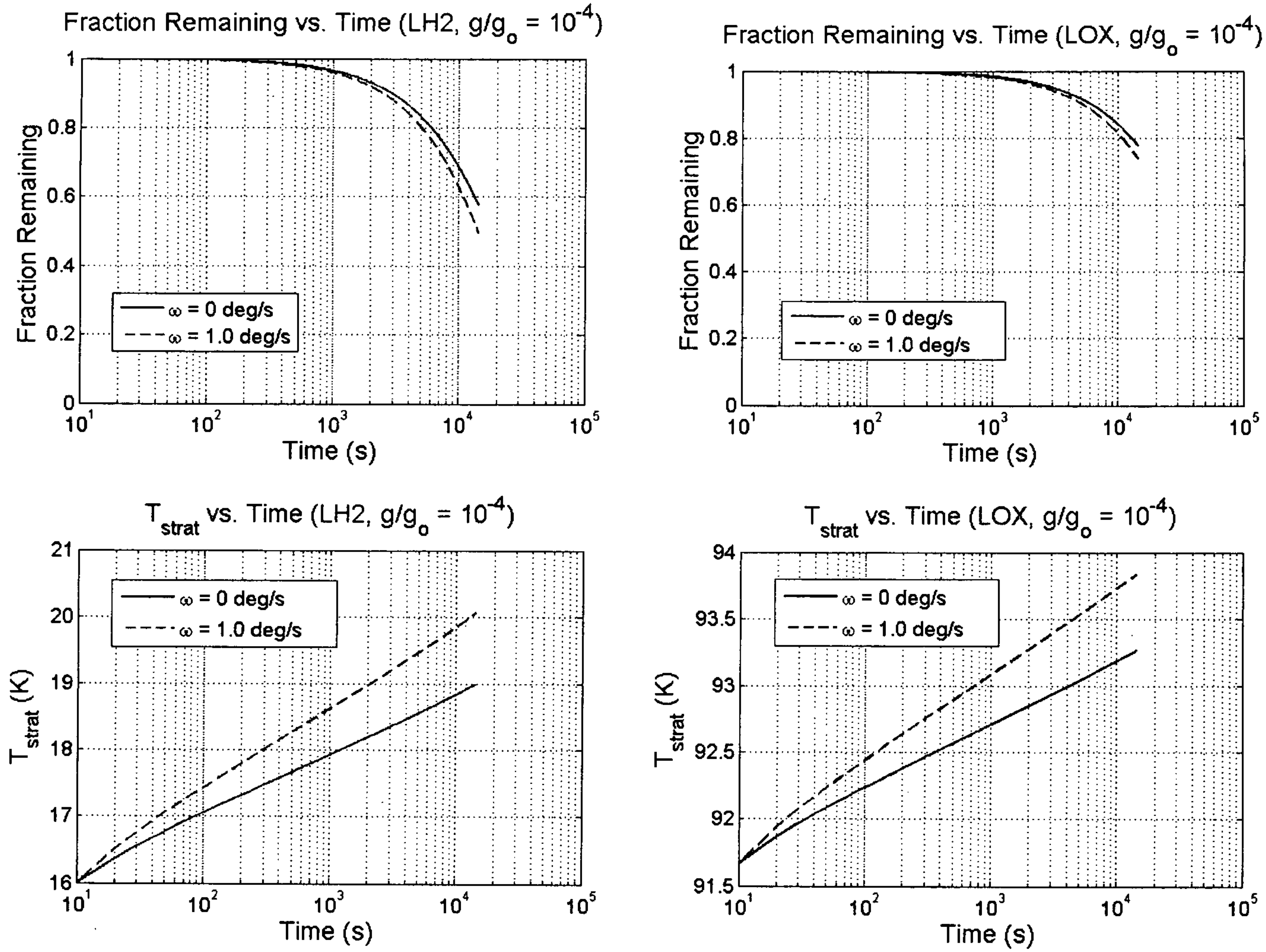
$$Gr^* = \frac{g\beta q_w\left(H + \frac{h}{2}\right)^4}{k\nu^2} = \frac{g\beta q_w\left(H_\omega\right)^4}{k\nu^2} \qquad \phi = \frac{\nu t}{H_\omega^2}$$

Re-derive energy balance to take into account additional heating area

$$\dot{q}\,2\pi R\left(H + \frac{h}{2}\right) = \dot{q}\,2\pi R H_\omega = \rho\pi R^2 \Delta c_p \frac{dT}{dt}$$



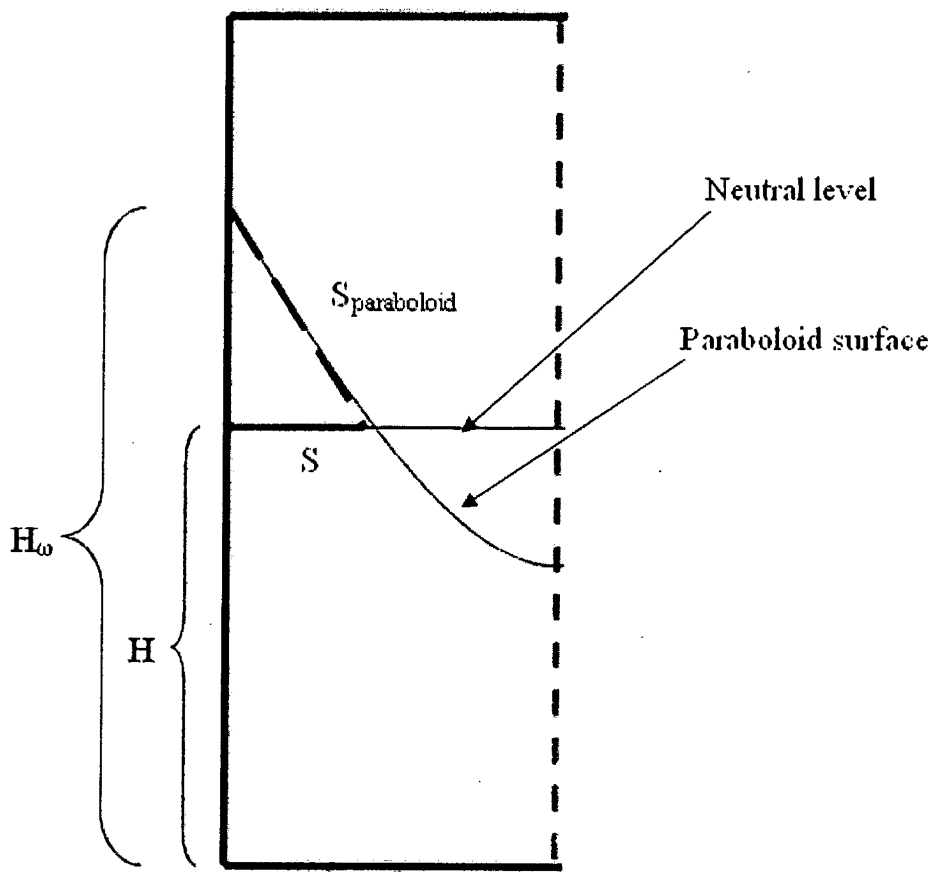
COMBINED ROTATION / STRATIFICATION MODEL: LH_2 and LOX



- For q=10 W/m^2, L=3, R=1.5, 20% fill level, H/R=0.4 and ω=1°/sec at $g/g_0=10^{-4}$:
  - Rotation decreases time to stratification time by ~ 15%
  - Rotation increases stratification temperature by ~ 1.0 K

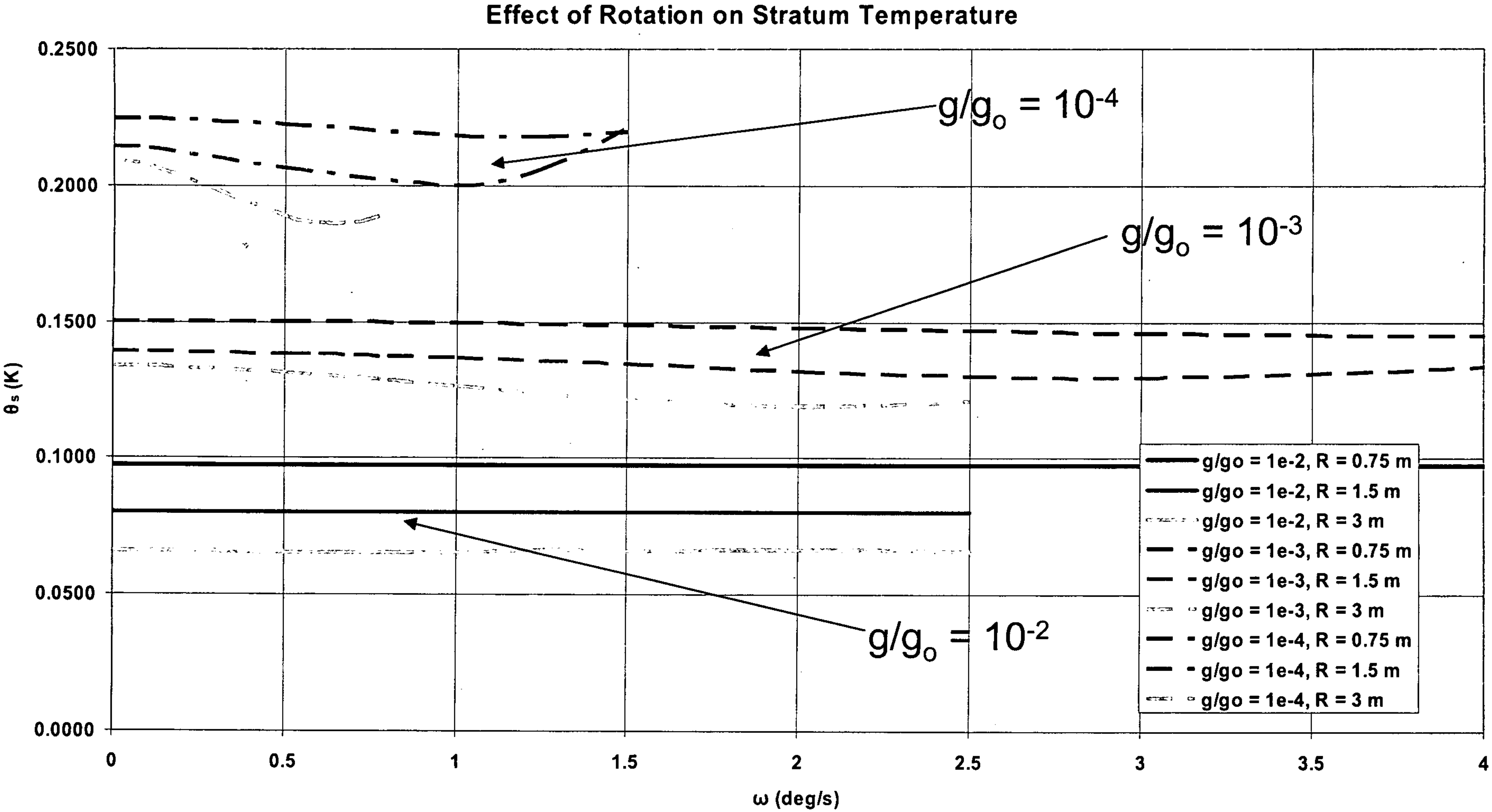
EFFECTS OF ROTATION AND TRADEOFFS

- Increased boundary layer running length ($H \rightarrow H_{\omega}$)
  - more heated area
  - larger Grashof number
- Larger surface area at bulk-stratum interface ($S \rightarrow S_{paraboloid}$)
  - increased mass flow rate into stratum layer
  - more area to spread mass flow



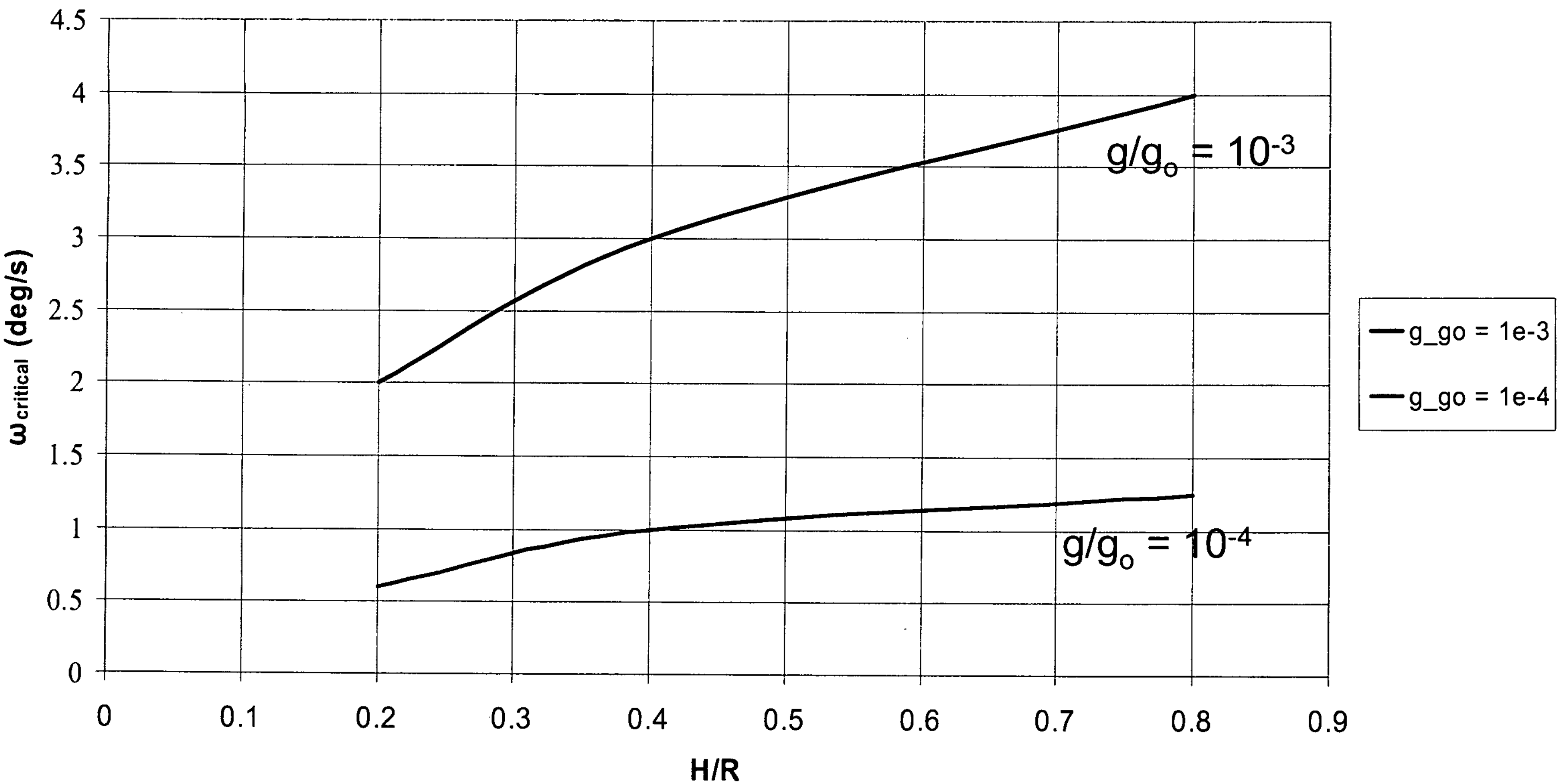
EFFECTS OF ROTATION

- Spinning always increases stratification
- Stratum temperature affected by spin rate; especially at low gravity levels
- LOX cases shown with heat flux of 5 W/m² after 2 hour mission



EFFECTS OF ROTATION

- $\omega_{critical}$ → spin rate to minimize stratum temperature
- $\omega_{critical}$ needed for large g/g_o impractical
- $\omega_{critical}$ needed for typical mission profiles very practical ($\omega < 1.5$ deg/s)
- LOX results discussed previously shown



SUMMARY/ CONCLUDING REMARKS

- Thermal stratification impacts T&P at conclusion of coast phase

- Rotation (creeping of fluid up side walls) has large effect for ω=1°/s and $g/g_0=10^{-4}$
  - 'Classical' literature model upgraded to include rotation effects
  - Can decrease time to stratify by 30-60 minutes during 4 hour coast
  - Larger heating area and lower liquid level above sump inlet
  - For various missions stratum temperature may increases or decrease relative to no-spin case
  - Mixed tank temperatures always larger because Δ increased with rotation

- Future work
  - Comparison with CFD studies

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