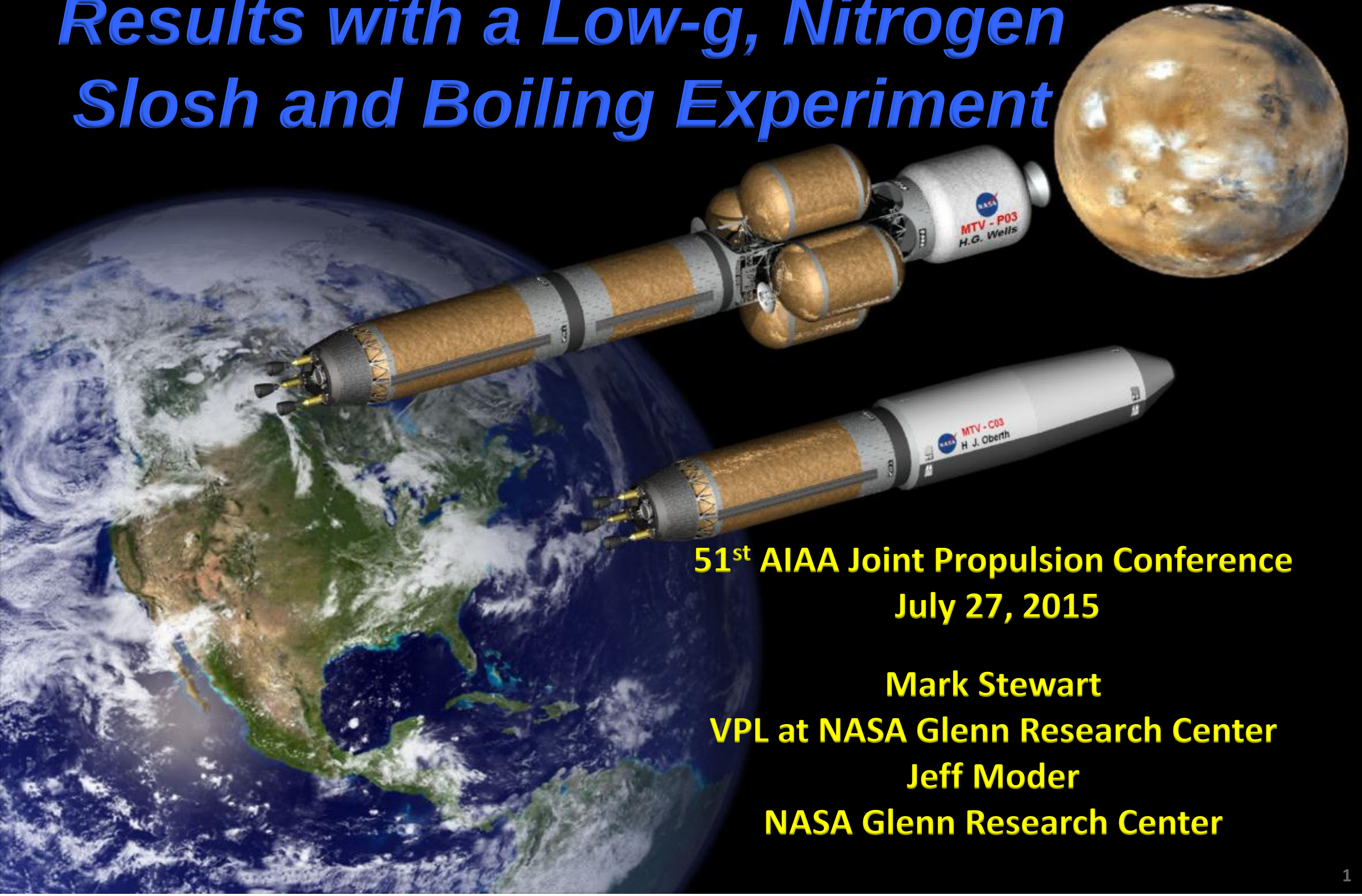
Comparison of Computational Results with a Low-g, Nitrogen Slosh and Boiling Experiment



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Mark Stewart
VPL at NASA Glenn Research Center
Jeff Moder
NASA Glenn Research Center

Outline

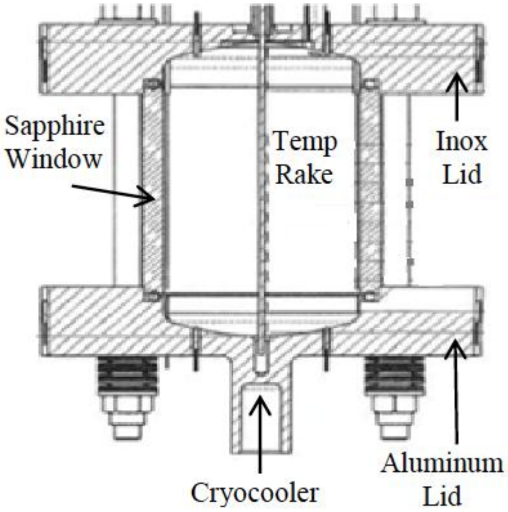
- Background and Motivation:
  - Cryogenic fluid behavior in flight conditions
  - Long-term, in-space storage of cryogenic propellants for future exploration missions

- Problem Setup:
  - Geometry & grid
  - Fluent settings
  - Fluid properties (N_2): temperature, pressure dependent?
  - UDF for condensation / evaporation
  - UDF for non-inertial reference frame
  - Time-dependent acceleration and Bond number
  - Boundary conditions
  - Procedure for initial conditions

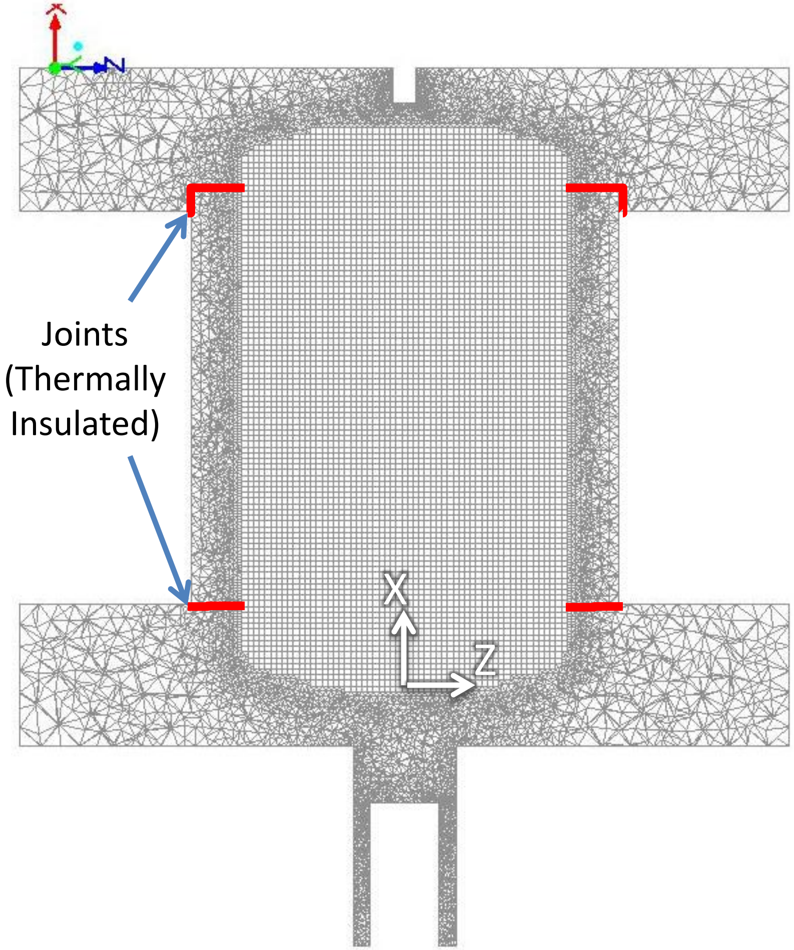
- Comparison with experimental data:
  - Initial thermal profile
  - Visual comparison with high-speed movie
  - Pressure data: balance of evaporation and condensation
  - Net heat transfer/boiling heat transfer rate
  - Comparison with temperature sensor data

Background & Motivation

- Background:
  - LN2 tank in 2010 low-g parabolic aircraft campaign
  - Significant condensation, evaporation, & boiling
  - Simulation compared to one low-g parabola
- Motivation:
  - Cryogenic fluid behavior in flight conditions
  - Long-term, in-space storage of cryogenic propellants for future exploration missions



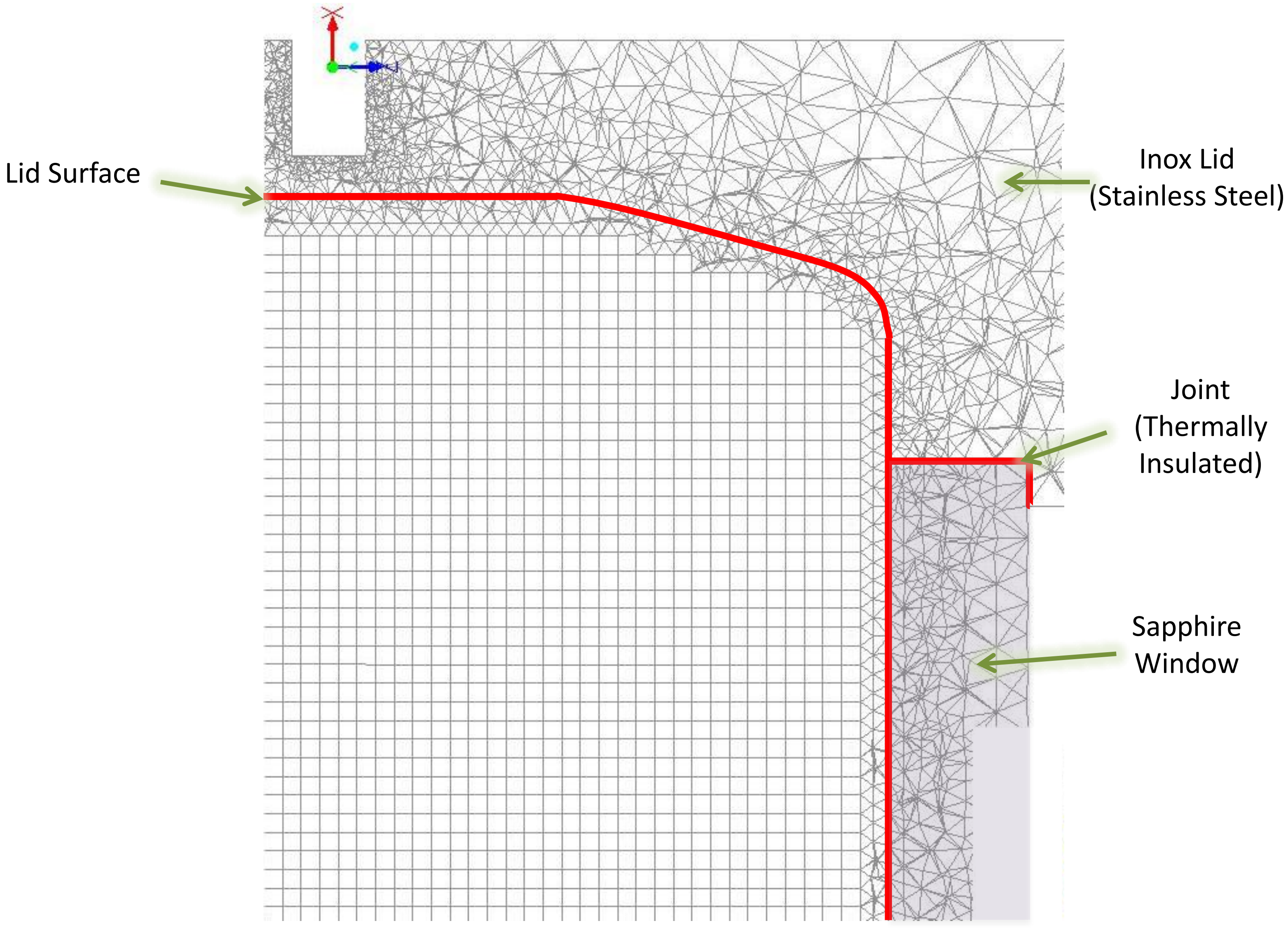
Geometry & Grid



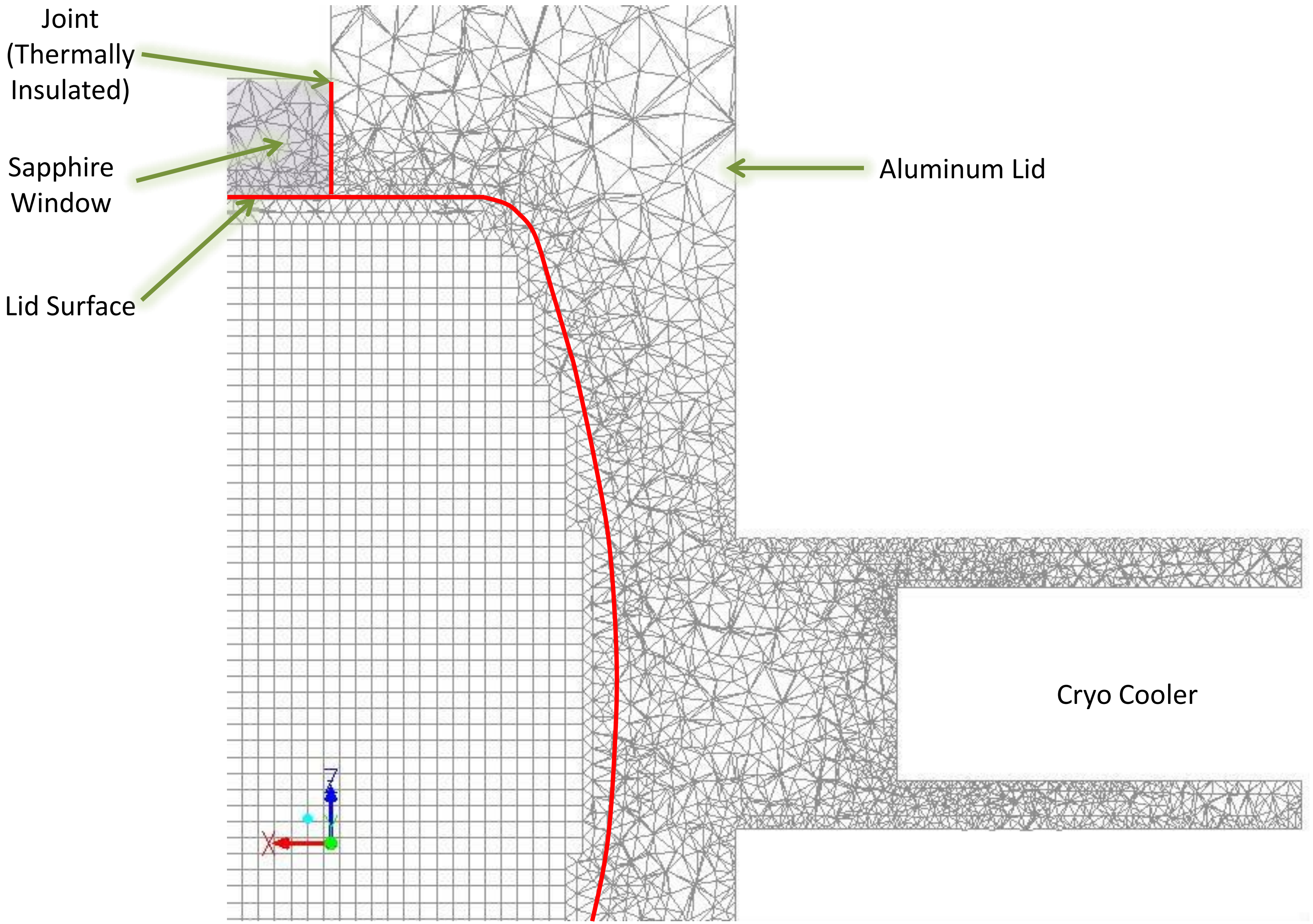
- 3-Dimensional grid, 360 degree sector
- Fluid Grid: 569,110 Cells
  - In interior, uniform, structured grid
  - 1 mm resolution
- Solid Grid: 685,858 Cells
  - Unstructured grid
  - Variable resolution
- Thermal isolation at joint, sealing gasket
- Post mounted temperature sensors, not simulated
- Currently, no refinement
- Partitioned for 16 or 32 processors

- Fluid tank dimensions:
  - Radius: ~3 cm
  - Height : ~10 cm
- Slosh frequency:
  - Observed ~4 Hz
  - Calculated 5.0 Hz

Geometry & Grid



Geometry & Grid



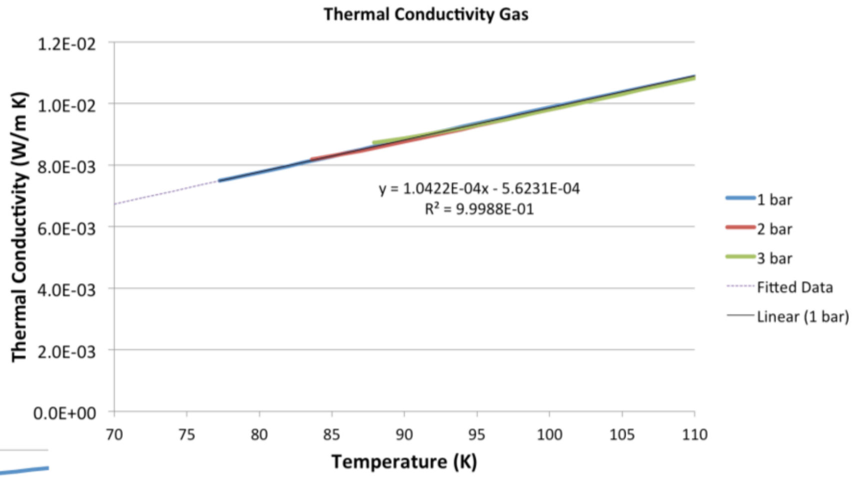
Fluent Setup for Simulations

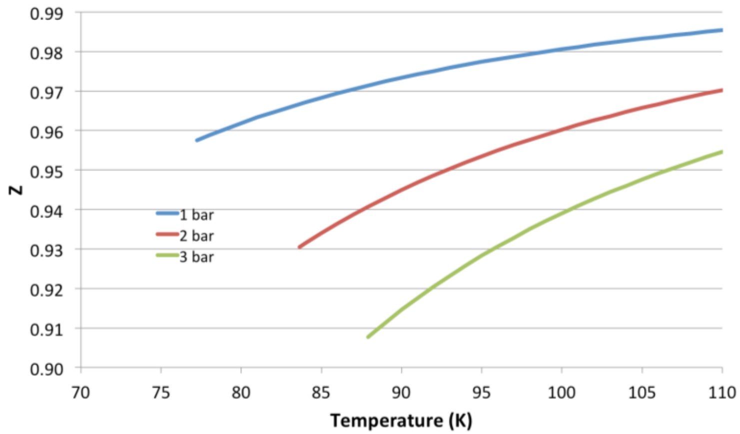
- Simulations performed using ANSYS Fluent version 13;
- 3D grid of fluid and solid regions
- Mass, momentum, energy, turbulence PDEs
- Compressible, ideal gas; Boussinesq liquid
- Fluid properties of nitrogen for fluid viscosity, thermal conductivity, specific heat, latent heat of vaporization, surface tension at 77.244K, 1 bar from webbook.nist.gov/chemistry/fluid
- Solid: temperature dependent density, specific heat, and thermal conductivity from CNES for inox (stainless steel), aluminum, and sapphire
- Volume of Fluid (VOF) for 2-phase flow
- k-ω SST turbulence model of Menter et. al. (turbulent damping = 10)
- UDF for mass transfer at liquid/ullage interface, boiling, and gas phase condensation
- UDF for non-inertial acceleration,
- Boundary conditions on later slide,

- Second order upwind scheme was used for discretization of the mass, momentum, energy, and turbulence, (cell values)
- PISO scheme was used for the pressure-velocity coupling (cell values)
- Least Squares Cell Based scheme was used for the gradient calculations (face values)
- PRESTO! scheme was used for the pressure interpolation (face values)
- First order implicit time discretization was used, also bounded second order implicit
- Time step = 1e-04 seconds
- Extensive instrumentation of the simulation

Temperature & Pressure Dependence of Fluid Properties

- Initially used constant properties for μ, κ, C_p, at 77.244K, 1 bar, but ~10% error
- Range of temperature and pressure: 70-110 K; 1 – 3 bar
- Well represented by simple polynomial in temperature:
  - Viscosity μ, (vapor & liquid)
  - Thermal conductivity κ (vapor & liquid)
  - Surface tension, γ
  - C_p liquid
- Varies with both temperature and pressure:
  - C_p gas
  - Heat of vaporization / condensation
  - Z varies ~8% (Ideal gas assumption)





Evaporation/Condensation UDF

- Mass transfer and heat of vaporization/condensation
- Based on Hertz-Knudsen-Schrage equation: $$\dot{m}_{net} = \frac{2}{2-\sigma_{cond}}\sqrt{\frac{MW_{vap}}{2\pi R_u}}\left(\sigma_{evap}\frac{P_{sat}(T_{liq})}{\sqrt{T_{liq}}} - \sigma_{cond}\frac{P_{vap}}{\sqrt{T_{vap}}}\right)$$
  - Derived from Maxwell dist'n

  kg/s-m^2 Evaporation is +ve
- Assume: $\sigma_{cond} = \sigma_{evap}$; $T_{vap} = T_{liq}$;
- *Constant(σ) * (P_{sat}(T) – P)/sqrt(T)/ length_scale* for local P, T
  - Enforces saturation conditions on interface
- UDF Define_Adjust() calculates mass transfer; UDF Define_Mass_Transfer() applies
- Requires kg/s-m^3, hence length_scale = sqrt(1/|grad c|^2), c is VOF fraction
- Different *situations*, different accommodation coefficients:
  - Interface condensation, $\sigma = 1.0\times10^{-4}$ is 'best' fit
  - Interface evaporation, $\sigma = 1.0\times10^{-4}$ is 'best' fit
  - Boiling (liquid phase evap), $\sigma = 5.0\times10^{-3}$ is 'plausible' fit
  - Gas phase condensation, $\sigma = 1.0\times10^{-4}$ is used
- Boiling—vaporization away from a liquid/vapor interface:
  - Superheat criteria in each cell: $T_{max} - T_{sat}(P) > 5$ K T_{max} is max in cell (walls too)
  - Dry boiling cut-off
- *P_{sat}(T)* by curve fit from Reynolds, *Thermodynamic Properties in SI*
- *T_{sat}(P)* curve fit to NIST data

Non-Inertial Reference Frame UDF

- Non-inertial reference frame accounts for:
  - Linear acceleration of aircraft, **a**
  - Angular rotation, **ω**, and angular acceleration, **α** (not present)

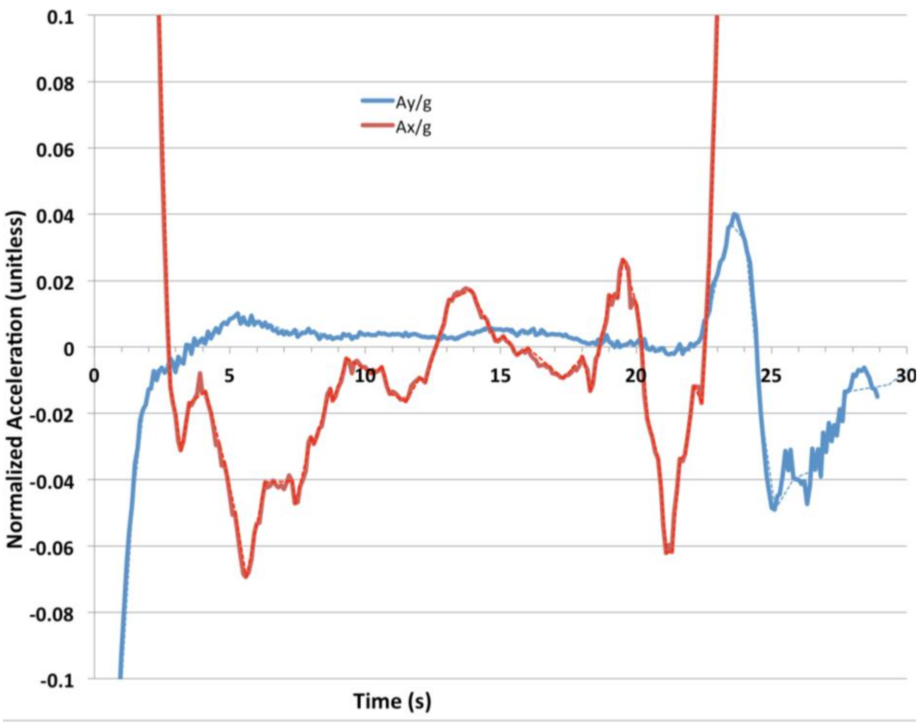
$$\vec{a}_{cg} + 2\vec{\omega} \times \vec{v_r} + \dot{\vec{\omega}} \times \vec{r} + \vec{\omega} \times (\vec{\omega} \times \vec{r})$$

  - In general, piece-wise linear fit to **a**, **ω**, $\mathbf{v}_r$ samples

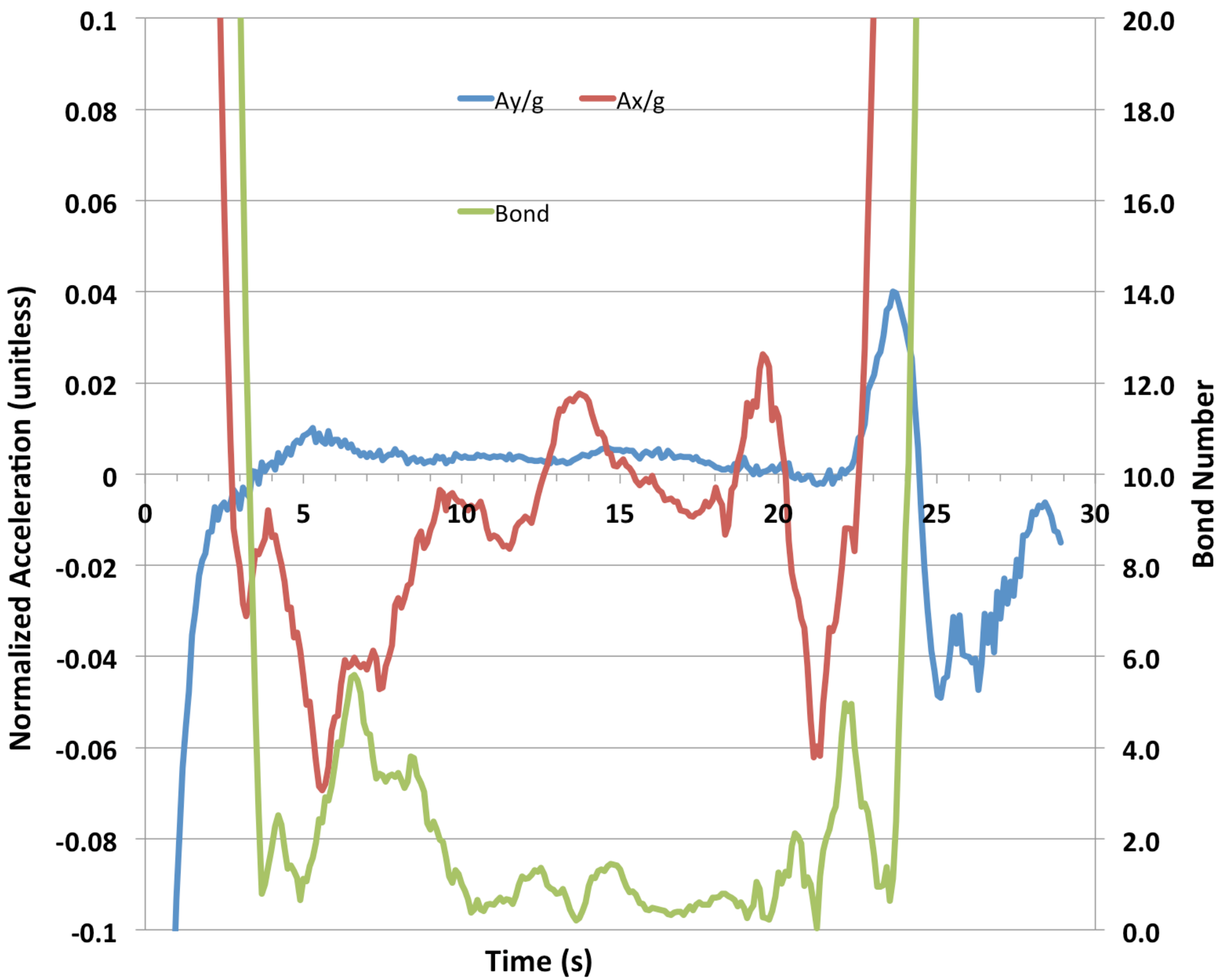
- Here, acceleration, **a**, sampled at 2 Hz, 10 Hz
  - Two components: a_x, a_z;   assume a_y= zero
  - Piece-wise linear fit to supplied a_x, a_z
  - Initial conditions: steady acceleration
    a_x=-16.5 m/s^2, a_y=0, a_z=-1.93 m/s^2

- UDF Define_Source adds terms to RHS of momentum equations as ρ **a**,   (kg m^2/s^2), and RHS of energy eqn. as   ρ **a•v**,   (kg m^3/s^3)

- Fluent has trouble with microgravity
  - Issues at O(a/g) ~ 10^{-6}
  - No issues at O(a/g) ~ 10^{-5}



Simulation Conditions: Bond Number

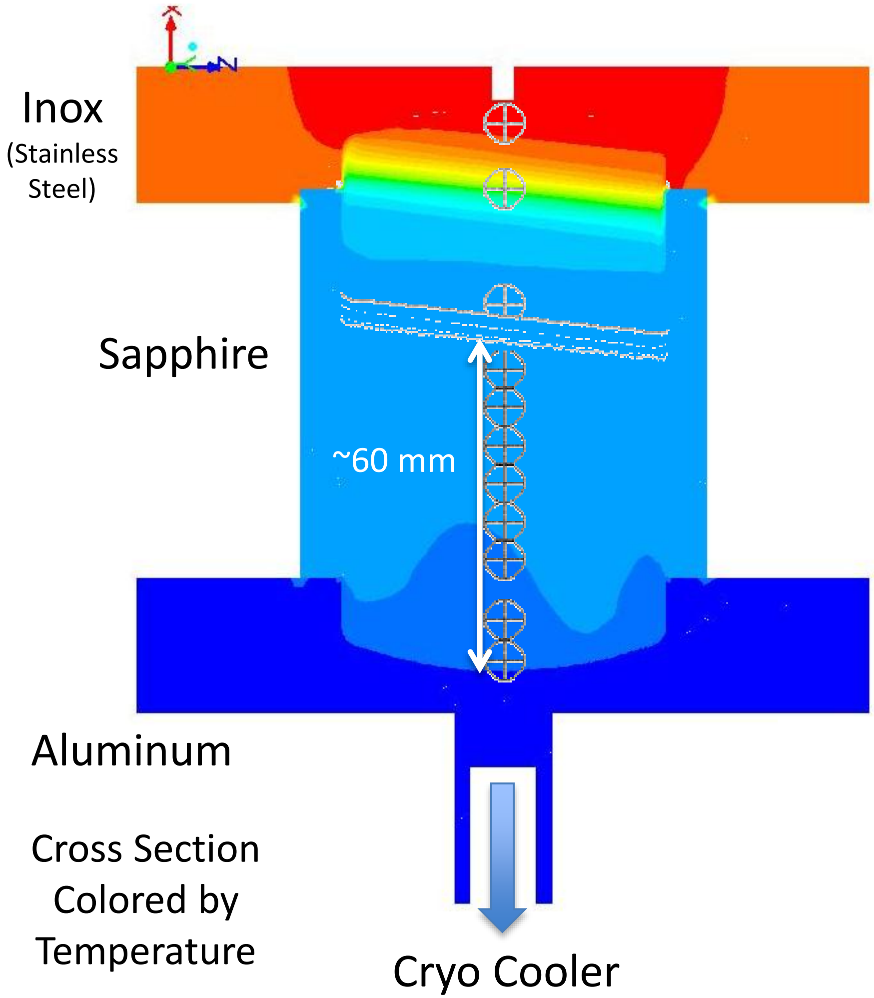


Bond number:

- Range [0.3, 6.]
- Mean 2.
- O(1) for 10 s
- Surface tension forces/ body forces
- Eötvös number

- Acceleration due to gravity at 10 Hz supplied by CNES
- 2 components: g_x, g_y

Boundary Conditions



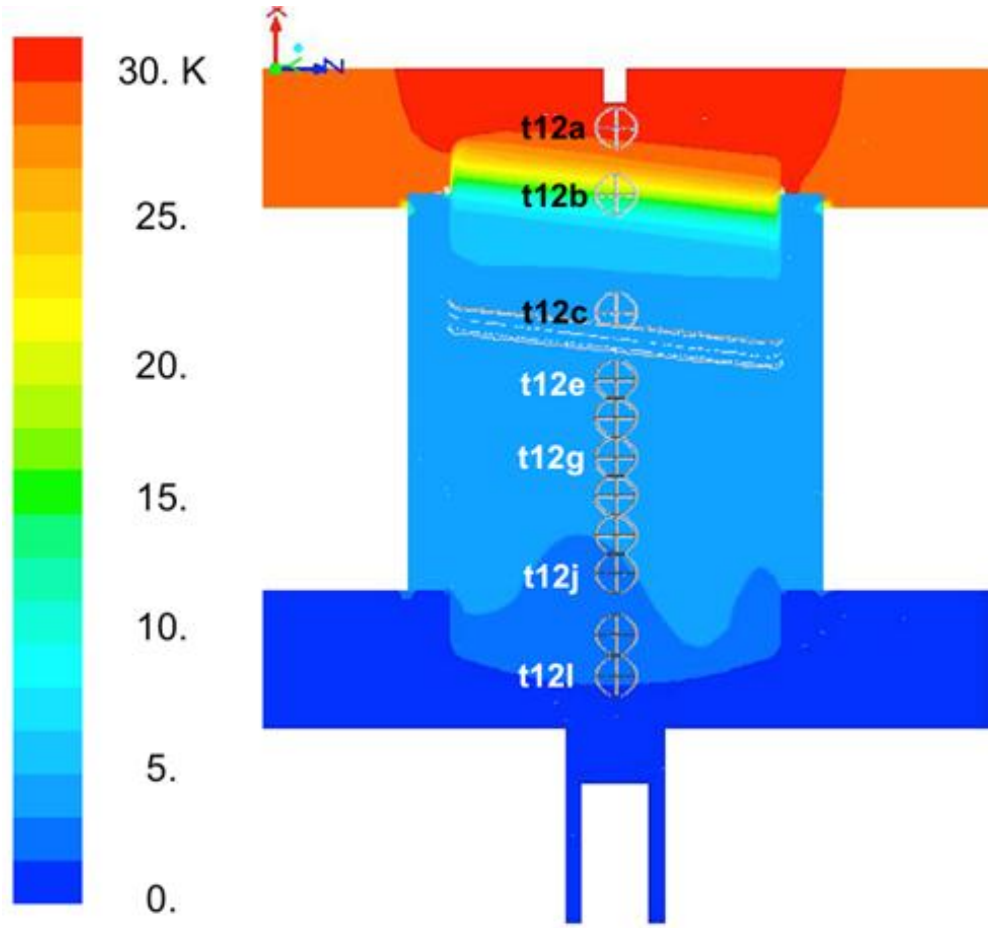
- Heat fluxes total ~4 W
- Assumed constant on surface of each part
- Due to radiation & conduction

- Liquid-to-vapor contact angle: 5 degrees

- Initial constant acceleration:
  - a_x = -16.4993 m/s^2; a_x/g = -1.682
  - a_y = 0.
  - a_z = -1.9325 m/s^2; a_z/g = -0.197

- Initial interface
  - Position: ~60 mm from bottom
  - Angle: from initial acceleration

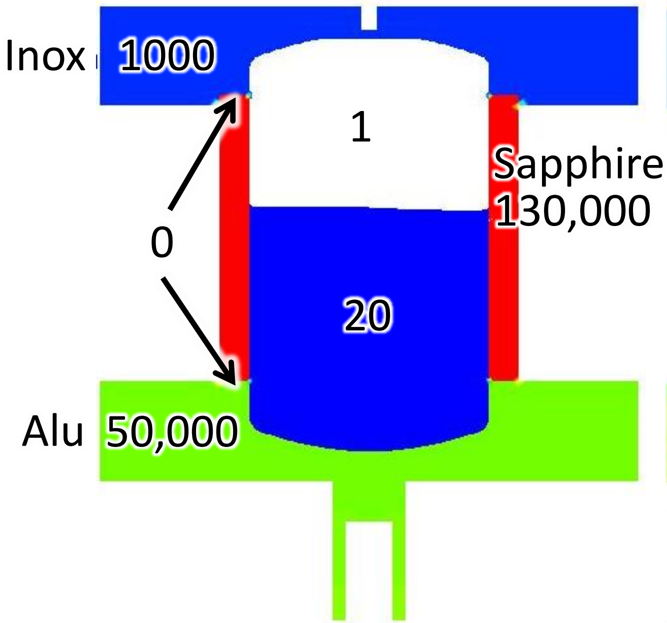
Initial Thermal Conditions



- Initial conditions by transient fluid-thermal simulation
  - Constant gravity
  - 90 s with time step of 4.0×10^{-4} s
- Thermal isolation at joints

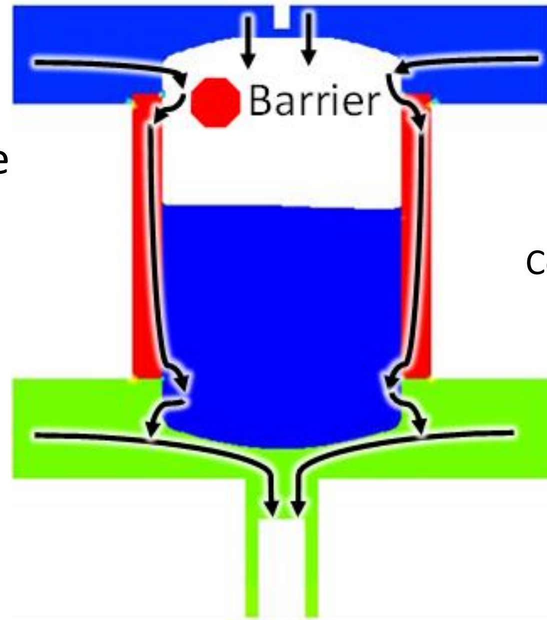
Temperature & Heat Flux: What & Why?

Relative Thermal Conductivity

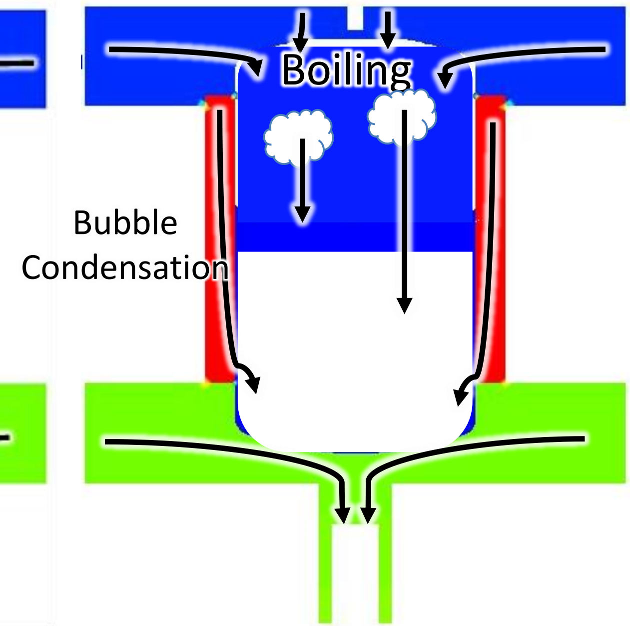


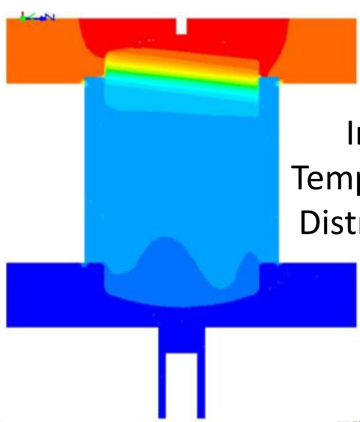
Initial Heat Flow

Heat Build-Up



Heat Flow in Re-Orientation





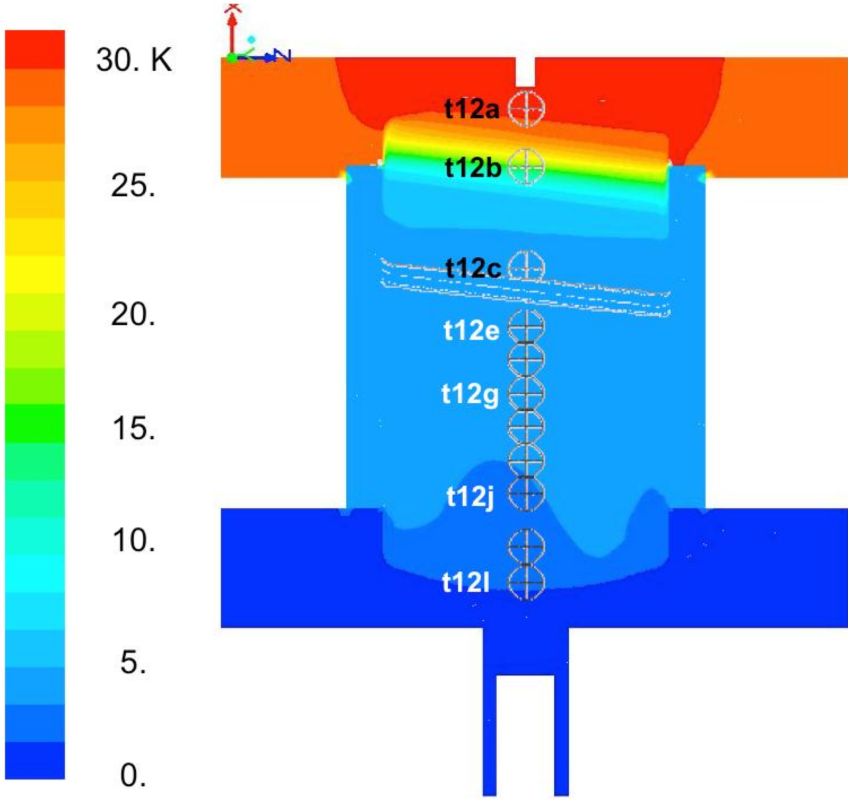
Initial Temperature Distribution

- Vapor and sealing gasket create insulation (high temperature gradient)
- Inox lid heats up in high-g interval with vapor at top
- With low-g, re-orientation, liquid impinges on hot lid, and boils
- Heat Transfer: surface boiling, departure of bubble, condensation
- Heat transferred into well-mixed liquid with high heat storage capacity

Section 2: Comparison with Experimental Data

- Initial temperature profile
- Visual comparison with high-speed movie
- Pressure data: balance of evaporation and condensation
- Net heat transfer/boiling heat transfer rate
- Comparison with temperature sensor data

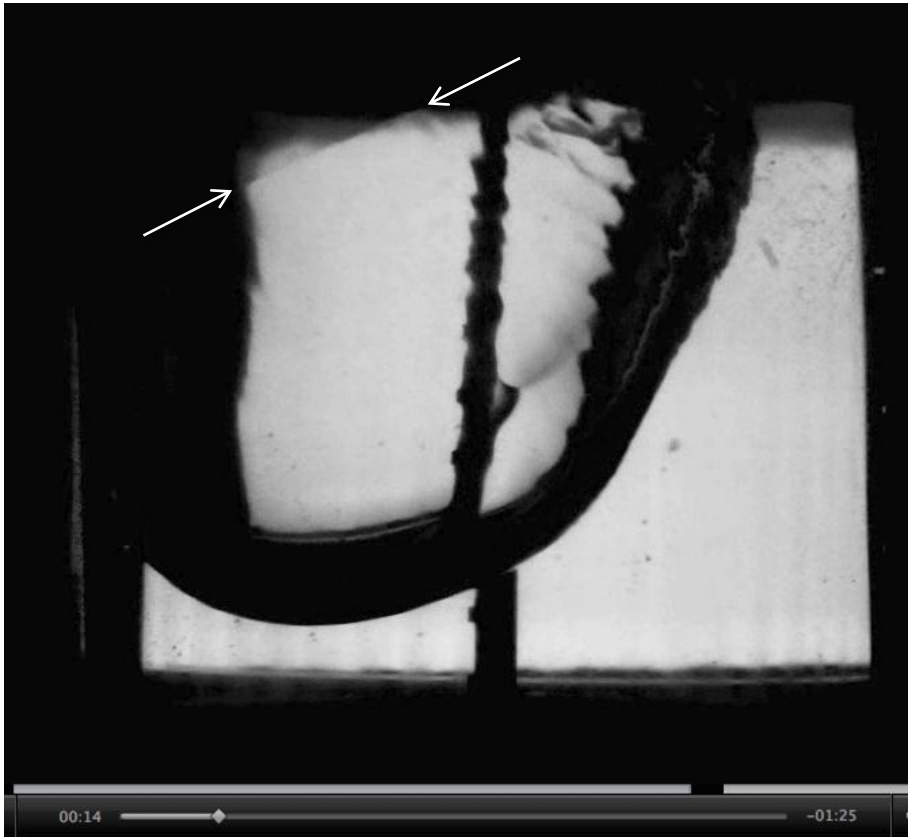
Initial Thermal Conditions



	Simulation Temperature, $T-T_0$ (K)	Percentage Difference (%)
Top Lid Center	31.4	
Top Lid Edge	30.0	
Top Lid Side	29.6	
t12a	30.4	0.3
t12b	15.2	3.4
t12c	4.4	0.9
t12d	4.2	0.9
t12e	3.5	0.0
t12f	3.4	-0.1
t12g	3.3	-0.2
t12h	3.3	-0.2
t12i	3.2	-0.2
t12j	3.0	-0.3
t12k	2.6	-0.1
t12l	2.6	0.4
Bottom Lid Center	1.6	

- Discrepancy near t12b in high temperature gradient: gasket modeling?
- Discrepancy near t12l and lower lid: specified heat fluxes?

Initial Re-orientation of Surface



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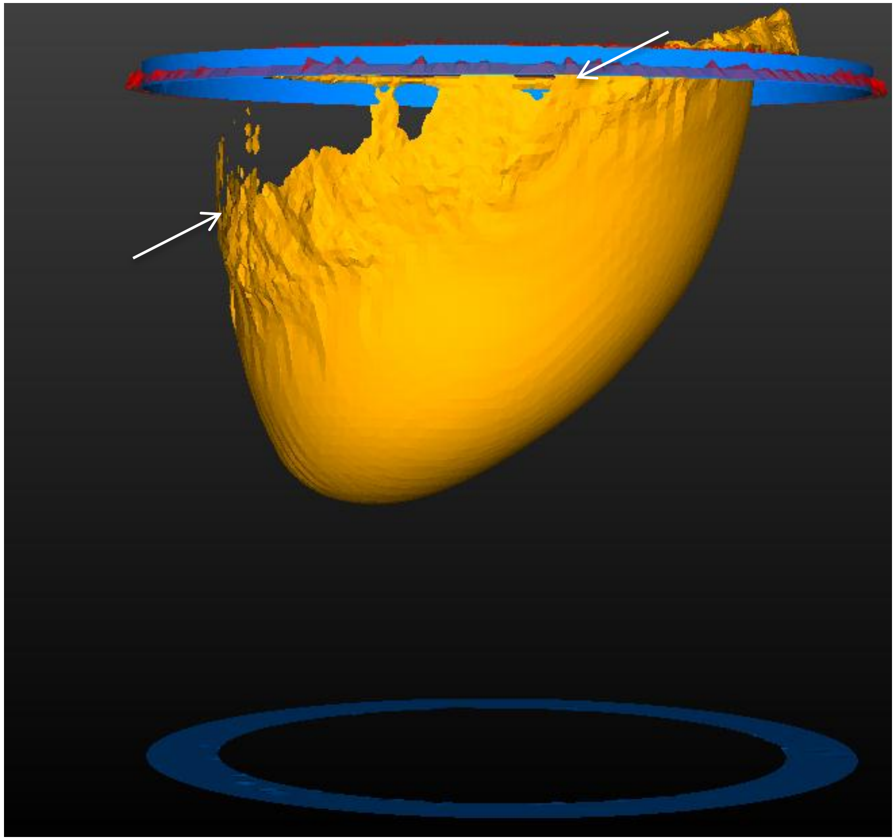
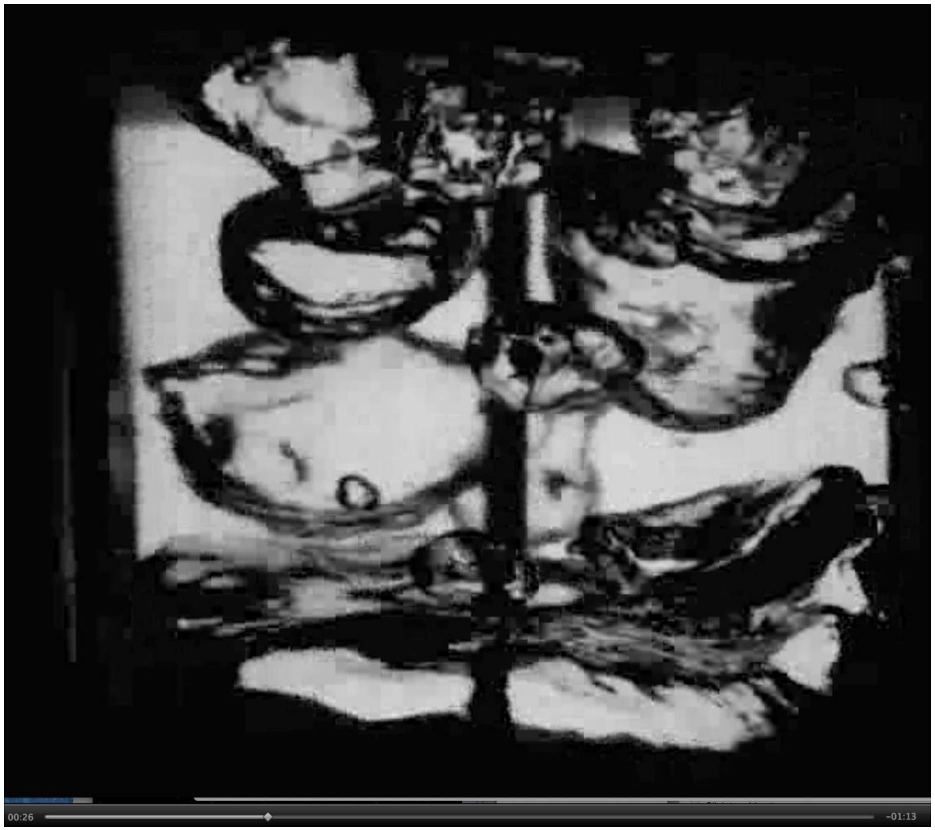


T=93.5 s in CNES_5C_7

Heavy Boiling Phase with Condensation and Transit



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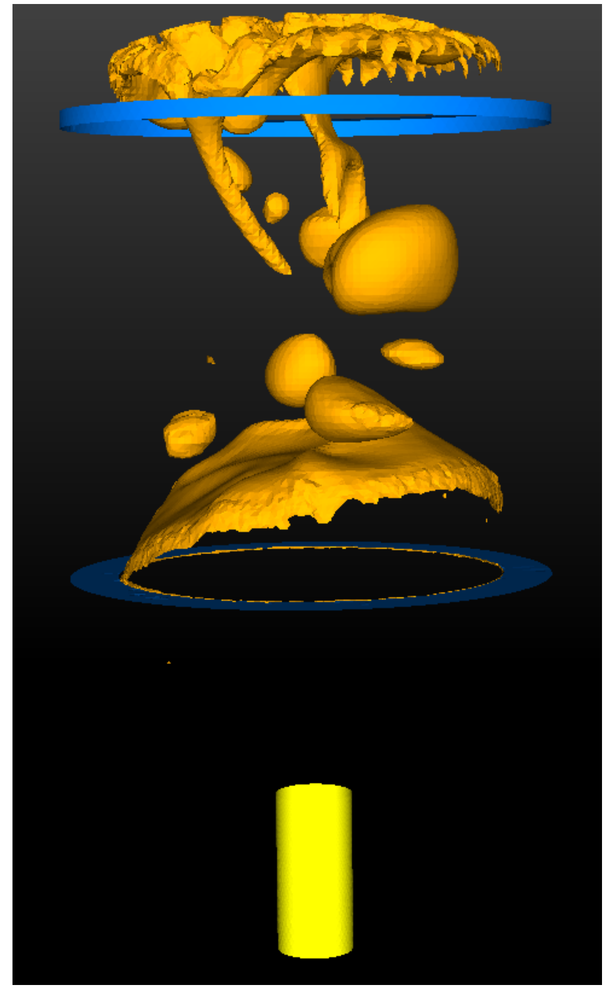
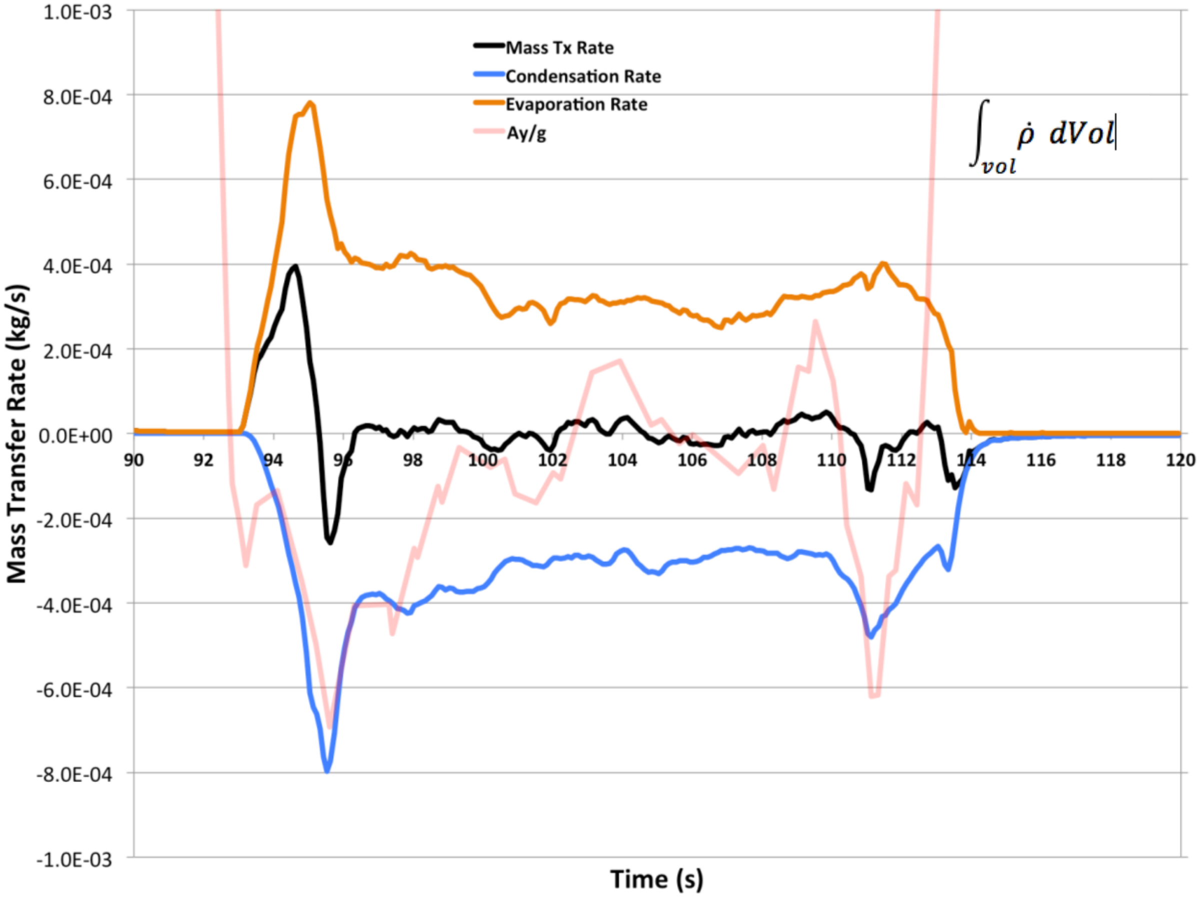
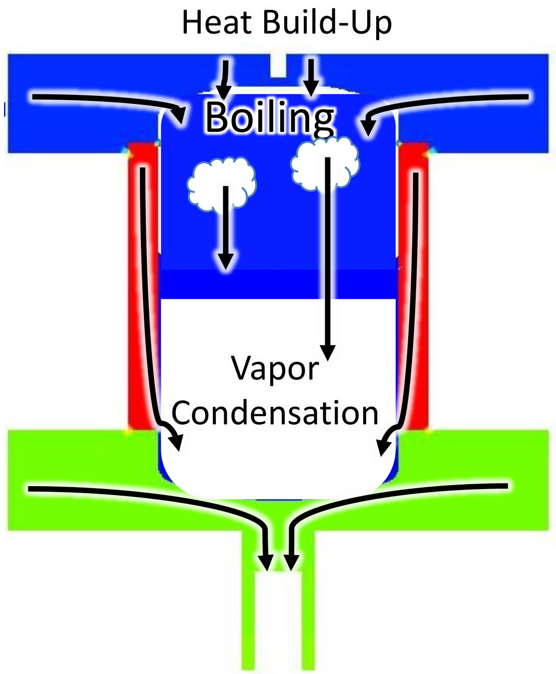


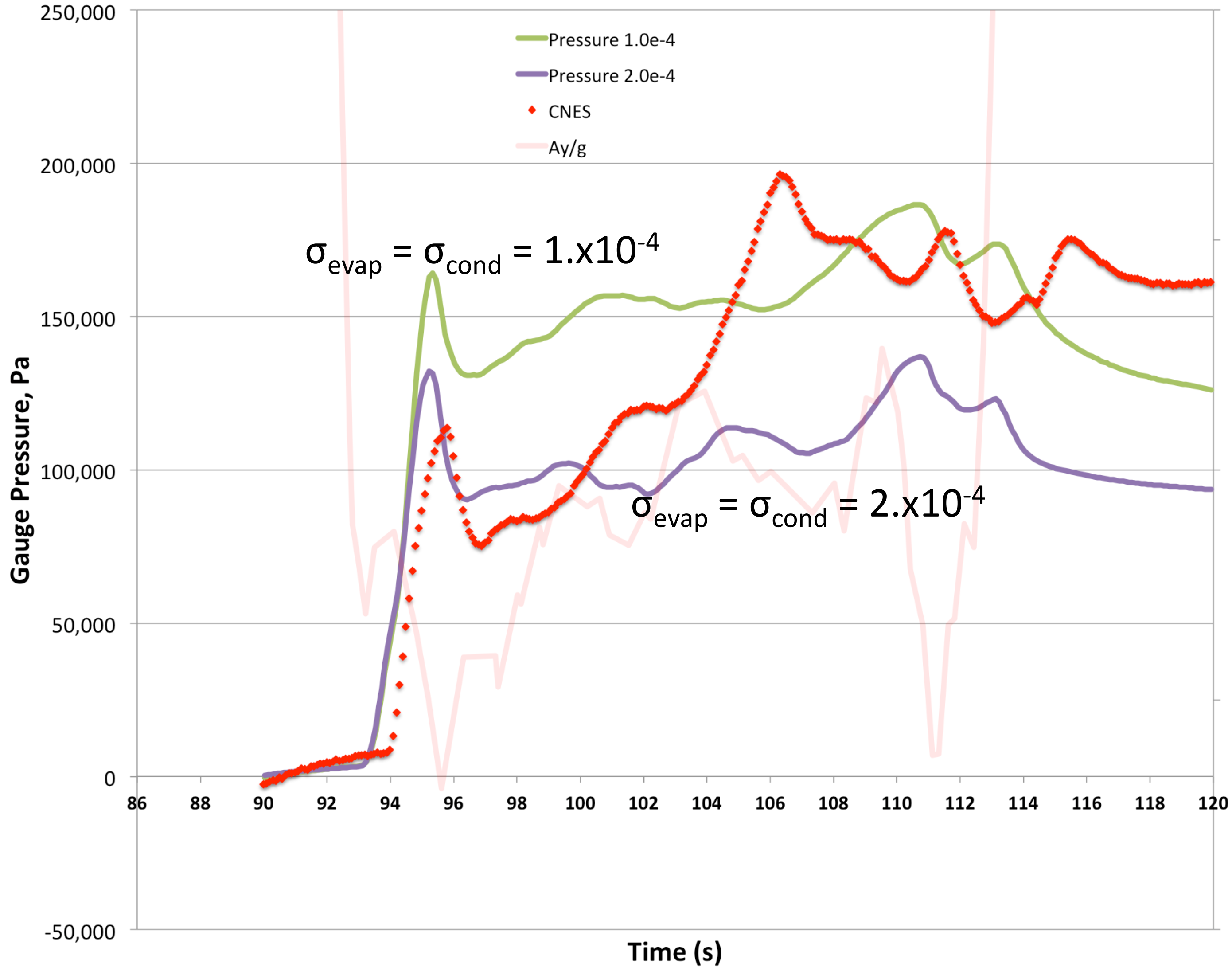
T=96.75 s in CNES_5C_7

Condensation and Evaporation: Both Large, Almost Cancel



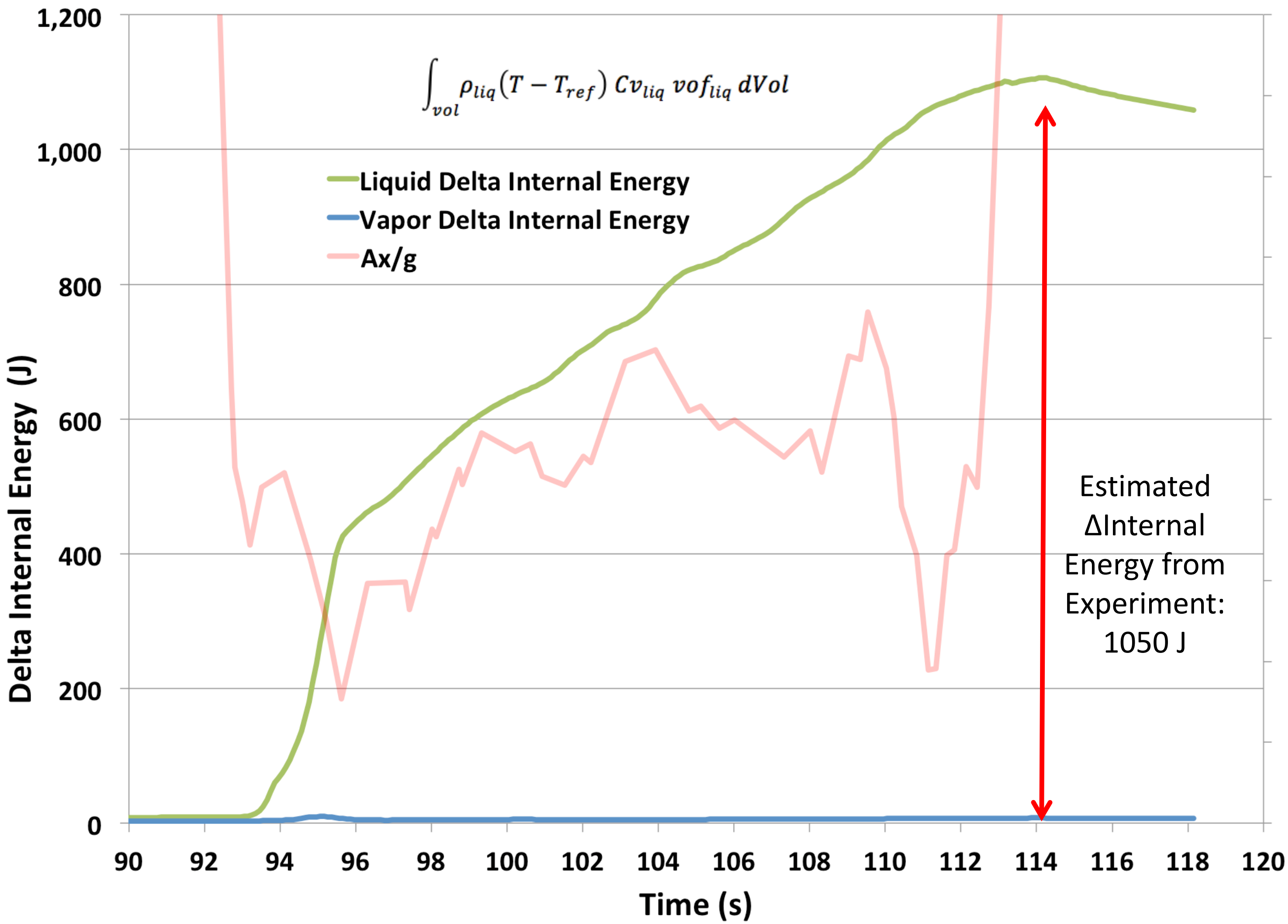


Pressure Evolution

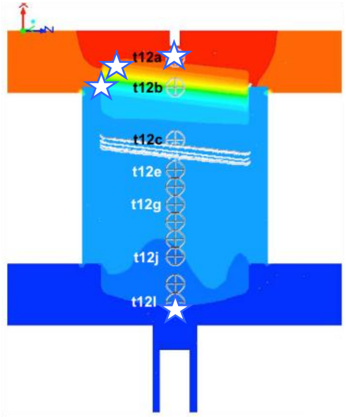


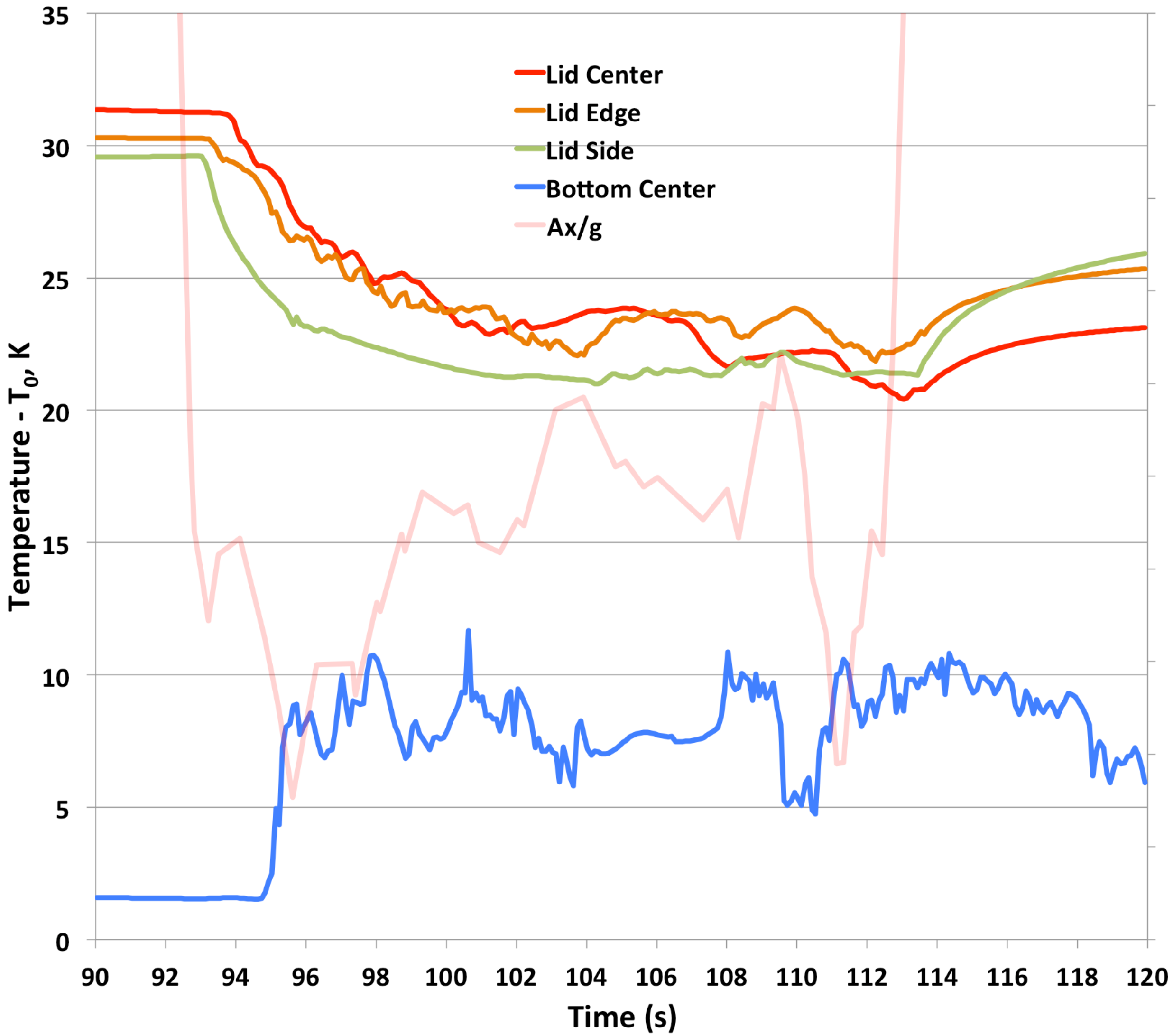
Internal Energy: A Measure of Heat Transfer

Is Boiling Heat Transfer Rate Correct?

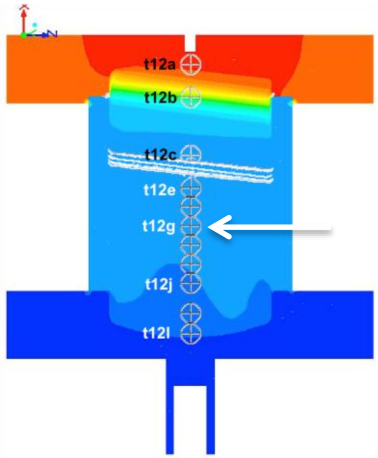


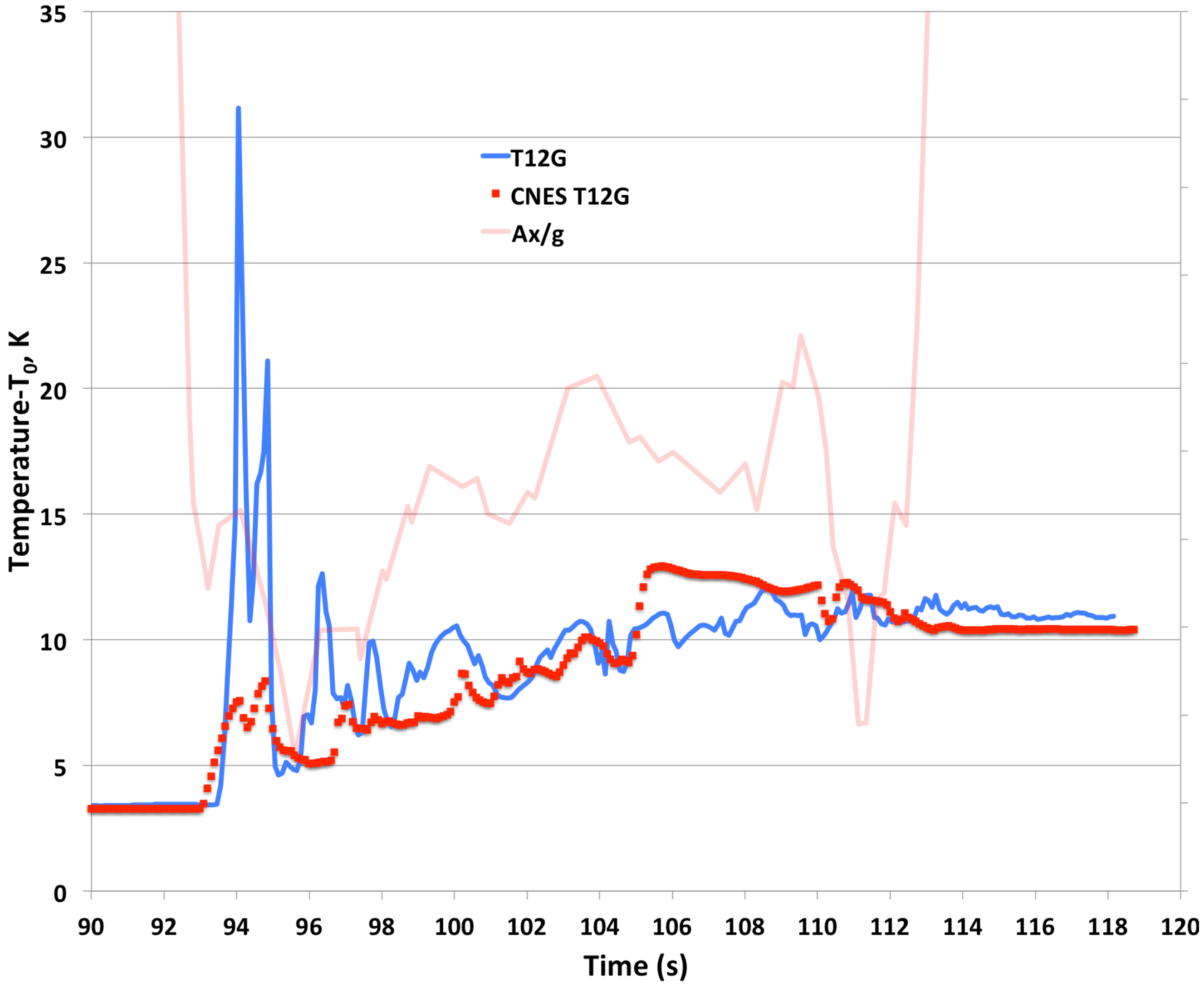
Results: Wall Temperatures



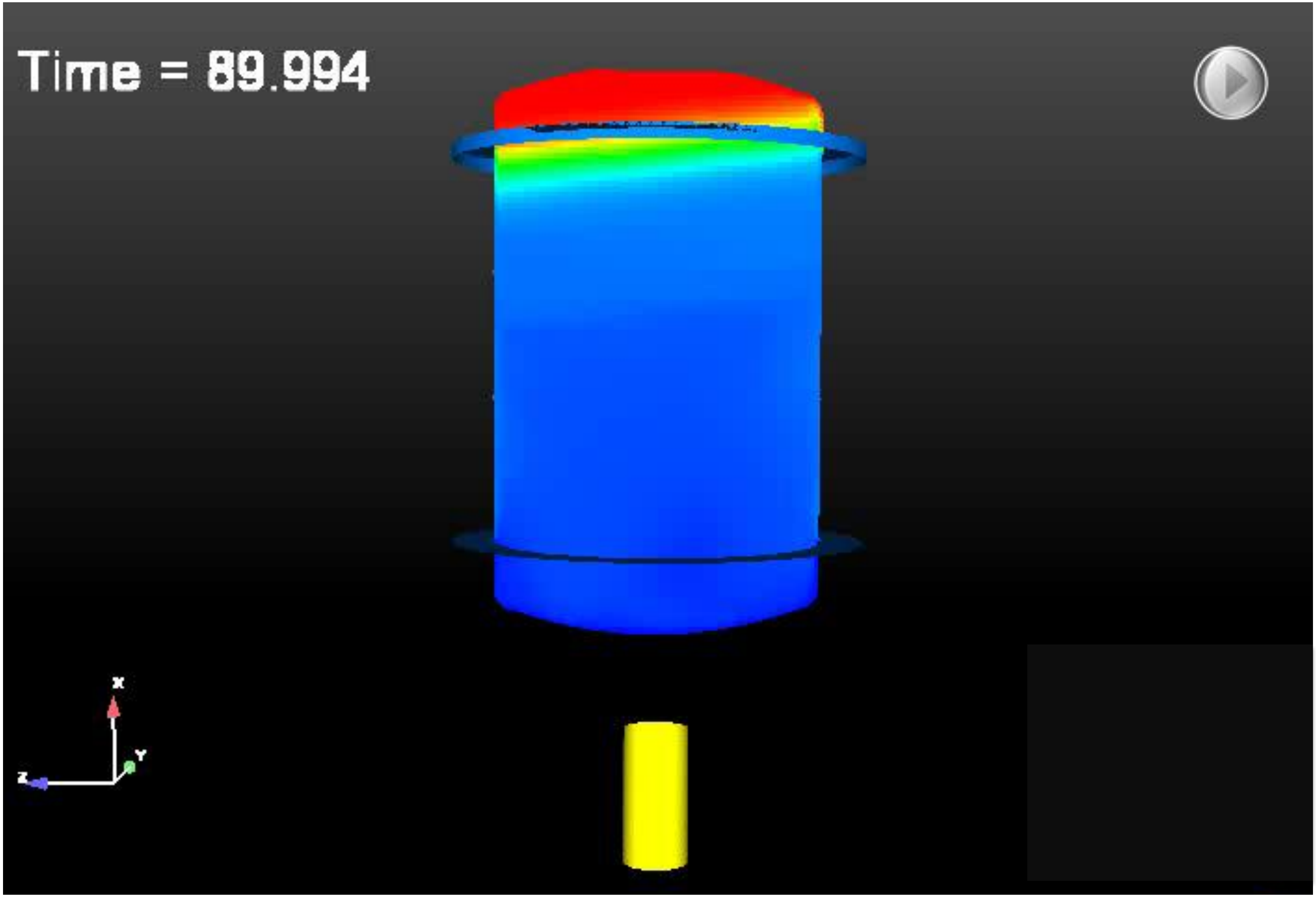


Results: Temperature Sensor T12G

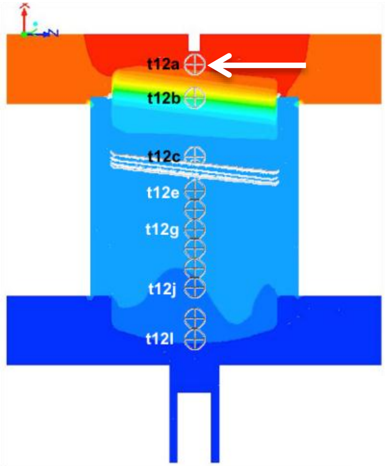


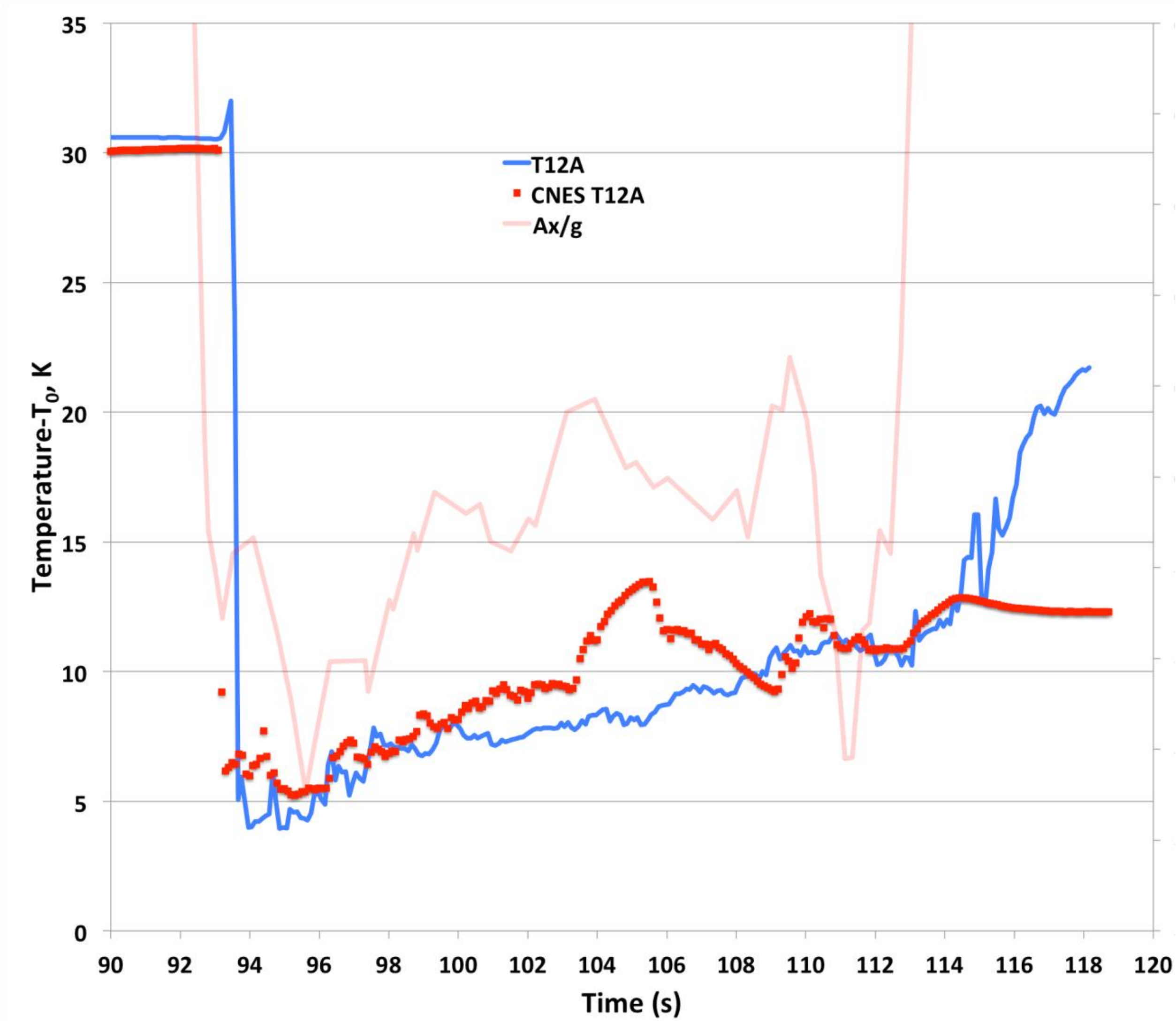


Fluid Temperature on Midplane

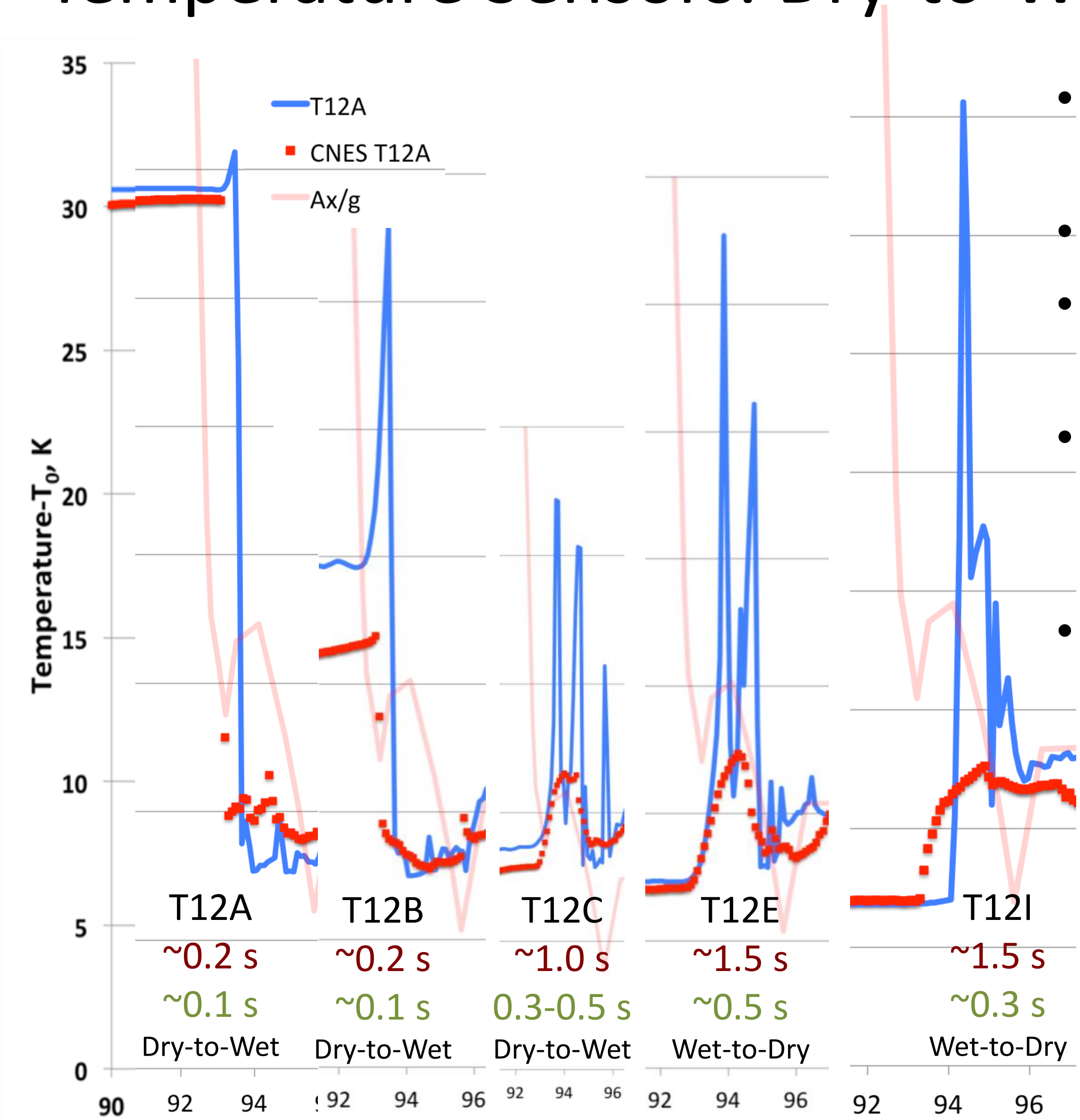


Results: Temperature Sensor T12A

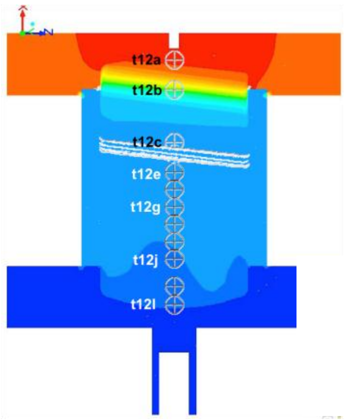




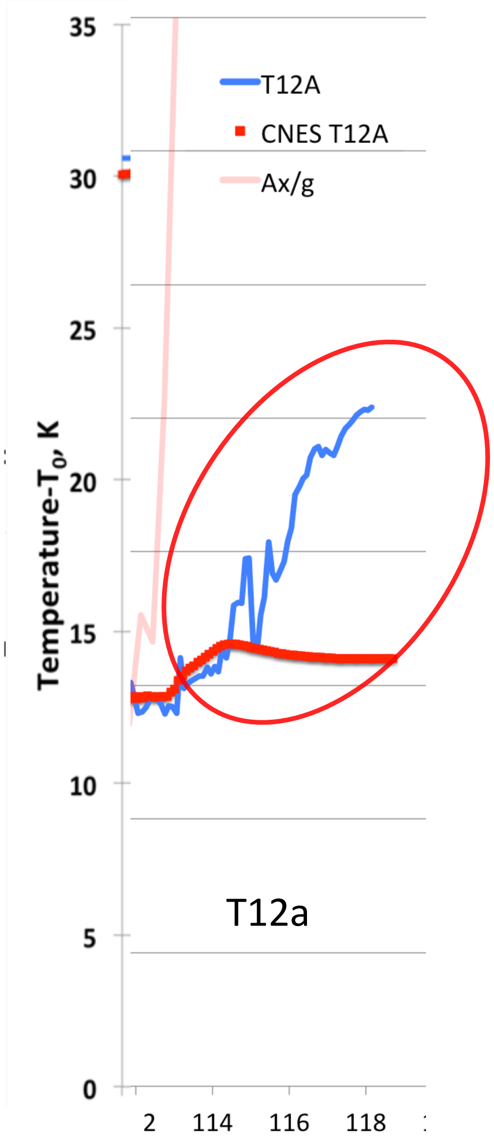
Temperature Sensors: Dry-to-Wet, Wet-to-Dry



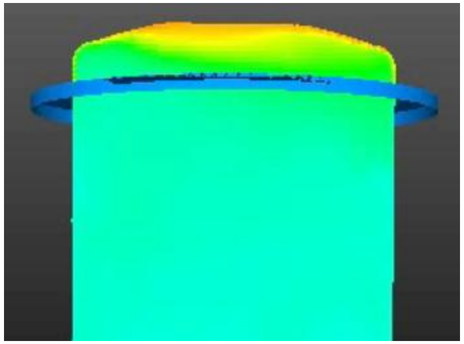
- Diode sensors time constant: $\tau = 0.1$ s
- 95% in 3 time constants, τ
- Hot gas exposure duration is 0.3 – 0.5 s (one-way)
- Wet-to-dry transition includes a liquid film that must vaporize, before gas
- Wet-to-dry time delays observed experimentally

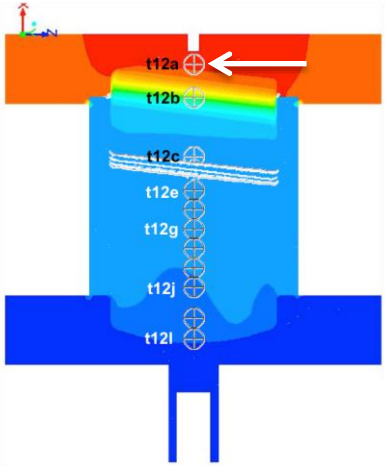


Sensors: Wet-to-Dry With Drainage



- Temperature discrepancy between T12a sensor (top) and simulation
- After low gravity phase (final re-orientation), as lid should be heating vapor to create a stable thermal stratification
- Experimental geometry is different: fill line and valve
- Wet-to-dry transition complicated by drainage?
- Drainage of liquid visible, in experiment, 2 s after final re-orientation
- Some simulations shows waves in thermal stratification, others do not





Summary

- Presentation: setup of Fluent and comparison with experimental results
  - Initial temperature profile
  - Visual comparison with high-speed movie
  - Pressure data
  - Net heat transfer/boiling heat transfer rate
  - Comparison with temperature sensor data
- Generally, good agreement with experimental data
- Evidence for low sensitivity of wet-to-dry temperature sensors
- Limitations of boiling model
- Limitation in prediction of condensation / evaporation
- Future work:
  - Further analysis of thermal layers near fluid/vapor interface
  - Grid resolution studies

BACKUP AND SUPPLEMENTARY