

Cryogenic Propellant Tank Self-Pressurization and Active Pressure Control

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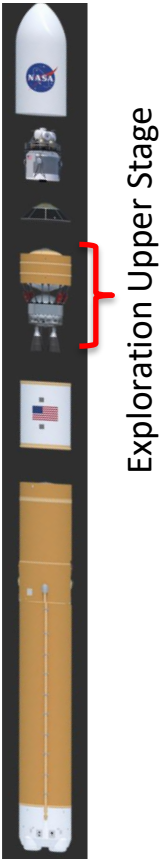


1. Introduction
 - i. NASA's CFM Requirements for Propellant Storage and Transfer
 - ii. Scientific & Technical Background
2. Computational Models for Propellant Tank CFM
3. Ground-Based Self-Pressurization Experiments and Model Simulation/Validation
4. Autogenous Tank Pressurization Experiments and Model Simulation/Validation
5. Ground- Based Pressure Control Experiments and Model Simulation/Validation
6. Slosh Dynamics & Pressure Collapse
7. Microgravity Self-Pressurization & Pressure Control Experiment and Model Simulation/Validation
 - i. Saturn IV
 - ii. Tank Pressure Control Experiment (TCPE)
8. ZBOT-1 Microgravity Experiment & Model Validation
 - i. Tank Self-Pressurization in μG
 - ii. Effect of Sudden Accelerations on Tank Pressurization
 - iii. μG Boiling at Hotspots During Self-Pressurization
 - iv. Jet-Ullage Interaction during Isothermal Jet Mixing - Turbulence Effects
 - v. Pressure Control with Subcooled Jet Mixing
9. ZBOT-NC: Effect of Noncondensable Pressurants
10. Closure

NASA's Future Exploration Missions Will Rely on Advanced CFM Technologies



Space Launch System (SLS)



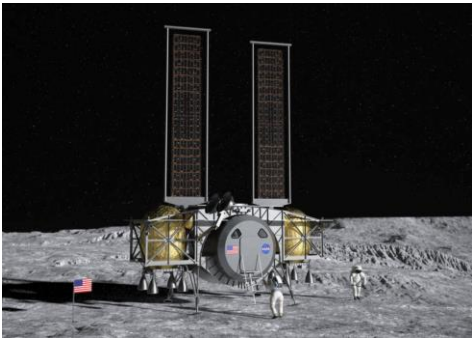
Exploration Upper Stage

Human Landing Systems (HLS)

Blue Origin



Dynetics

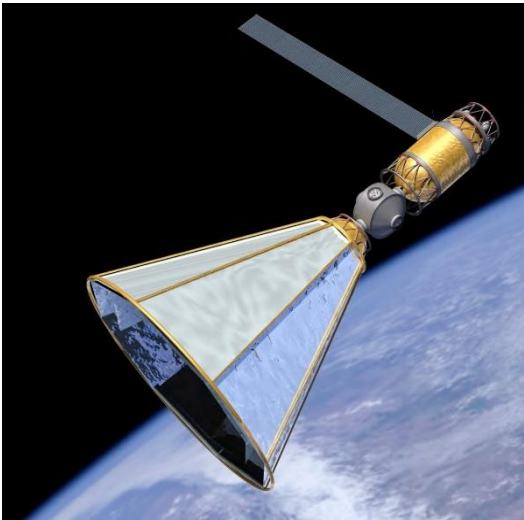


SpaceX

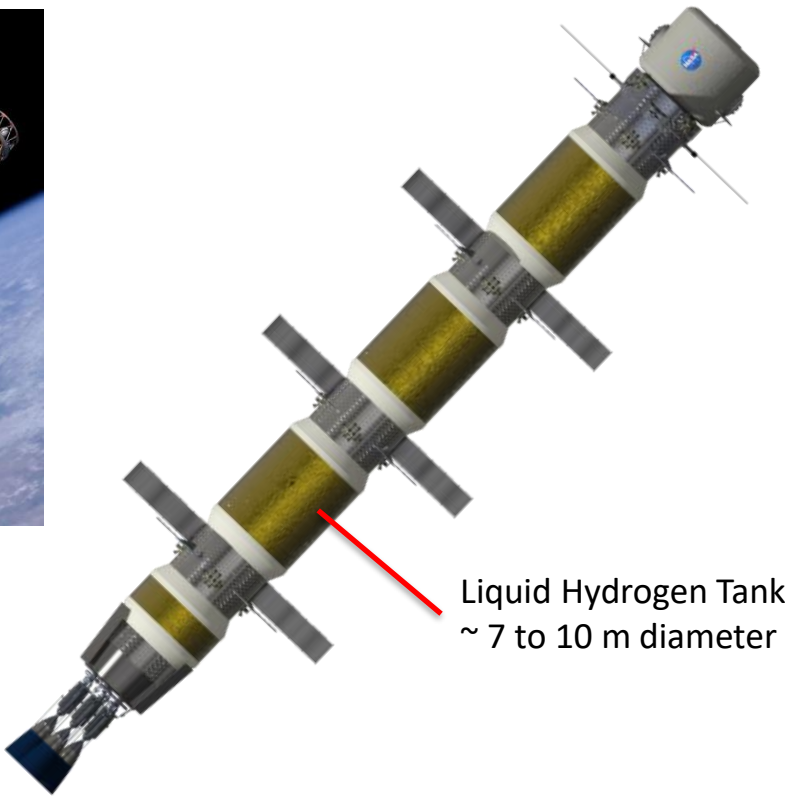


<https://www.nasa.gov/feature/nasa-selects-blue-origin-dynetics-spacex-for-artemis-human-landers>

In-Space Refueling of Transportation or Landing Vehicles



Nuclear Thermal Propulsion (NTP) Vehicle Concept for Crewed Conjunction Class Mission



Liquid Hydrogen Tank
~ 7 to 10 m diameter

Image Credit: Aerojet Rocketdyne, 2020 FISO Briefing



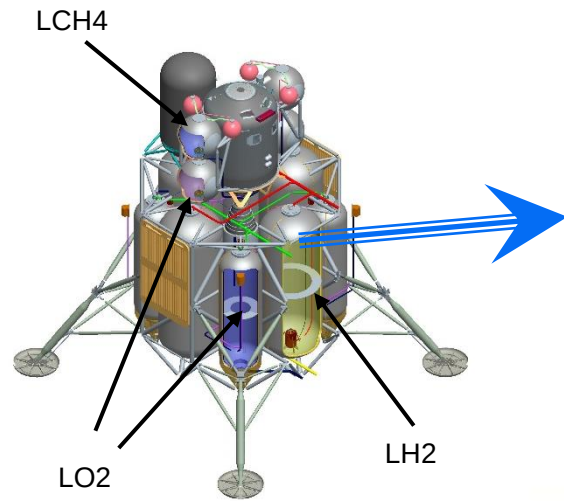
In-Space Vehicle Cryogenic Propellant Storage and Transfer



Green highlighting =

Non-Condensable gas influences CFM function

Conceptual Lander Tank Configuration



Cryogenic Tank Details

Pressurization

- Storage/compression
 - Helium
 - Autogenous
- Submerged injection

Pressure Control

- Low-g mixing/venting (thermodynamic vent and heat exchanger)

Liquid Acquisition

- Capillary retention devices for low-g
- Settling thrust

Lightweight Cryogenic Tank

- Metallic (Al-Li)
- Composite

Propellant Gauging

- Settled propellant
- Inventory (Bookkeeping)
- High accuracy low-g techniques

Liquid Transfer

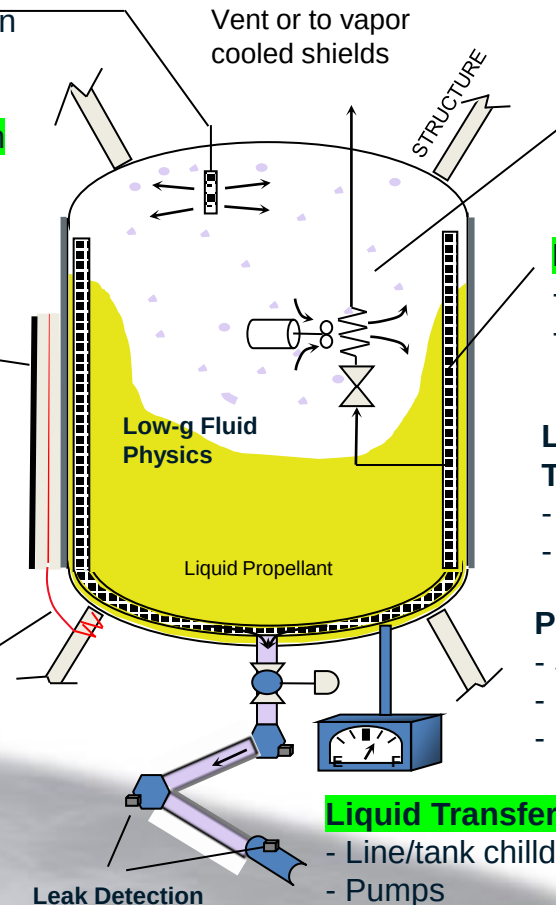
- Line/tank chilldown
- Pumps
- Leak-free coupling
- Operations

Passive Thermal Control

- Insulation (launch environments and in-space, MMOD protection)
- Sunshields
- Low conductivity/ vapor cooled support structure

Active Thermal Control

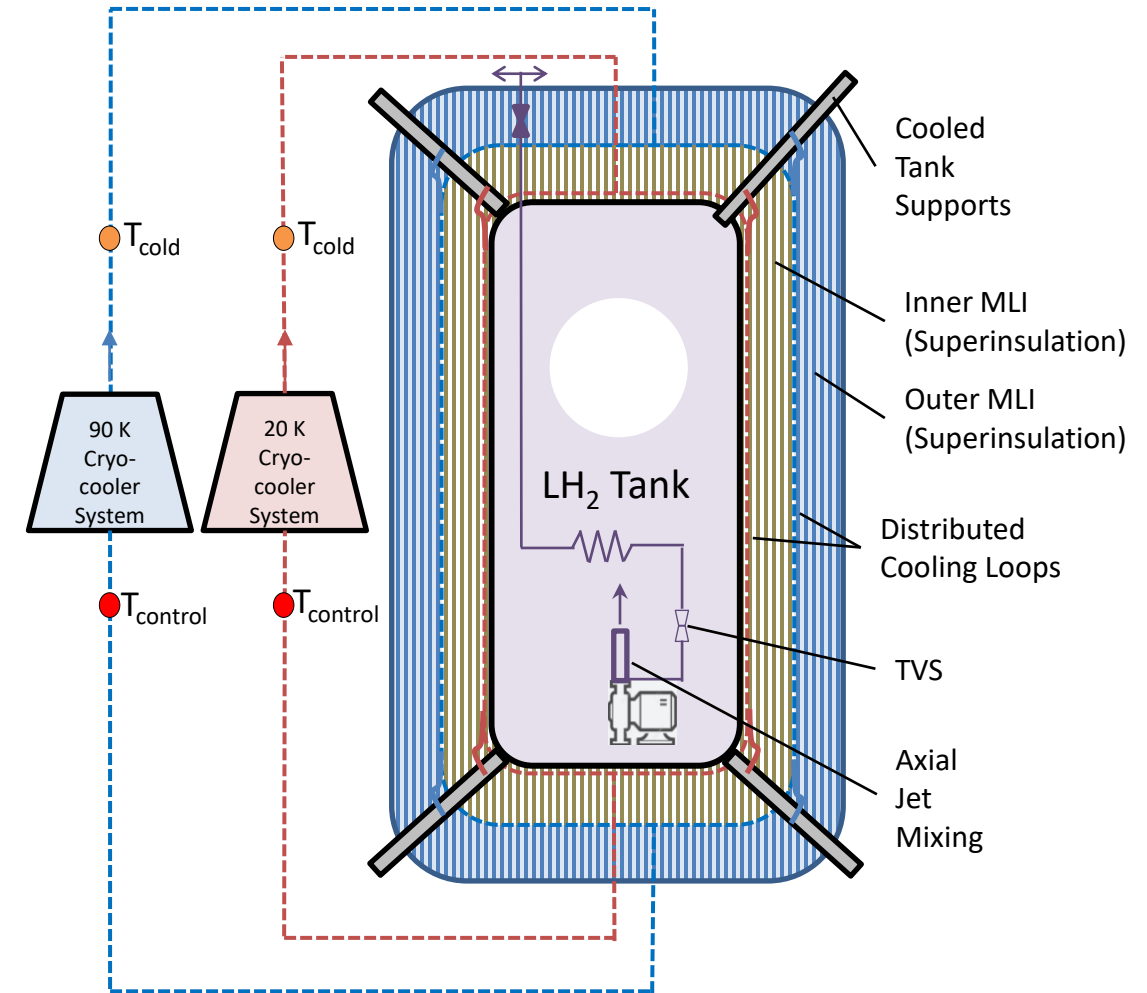
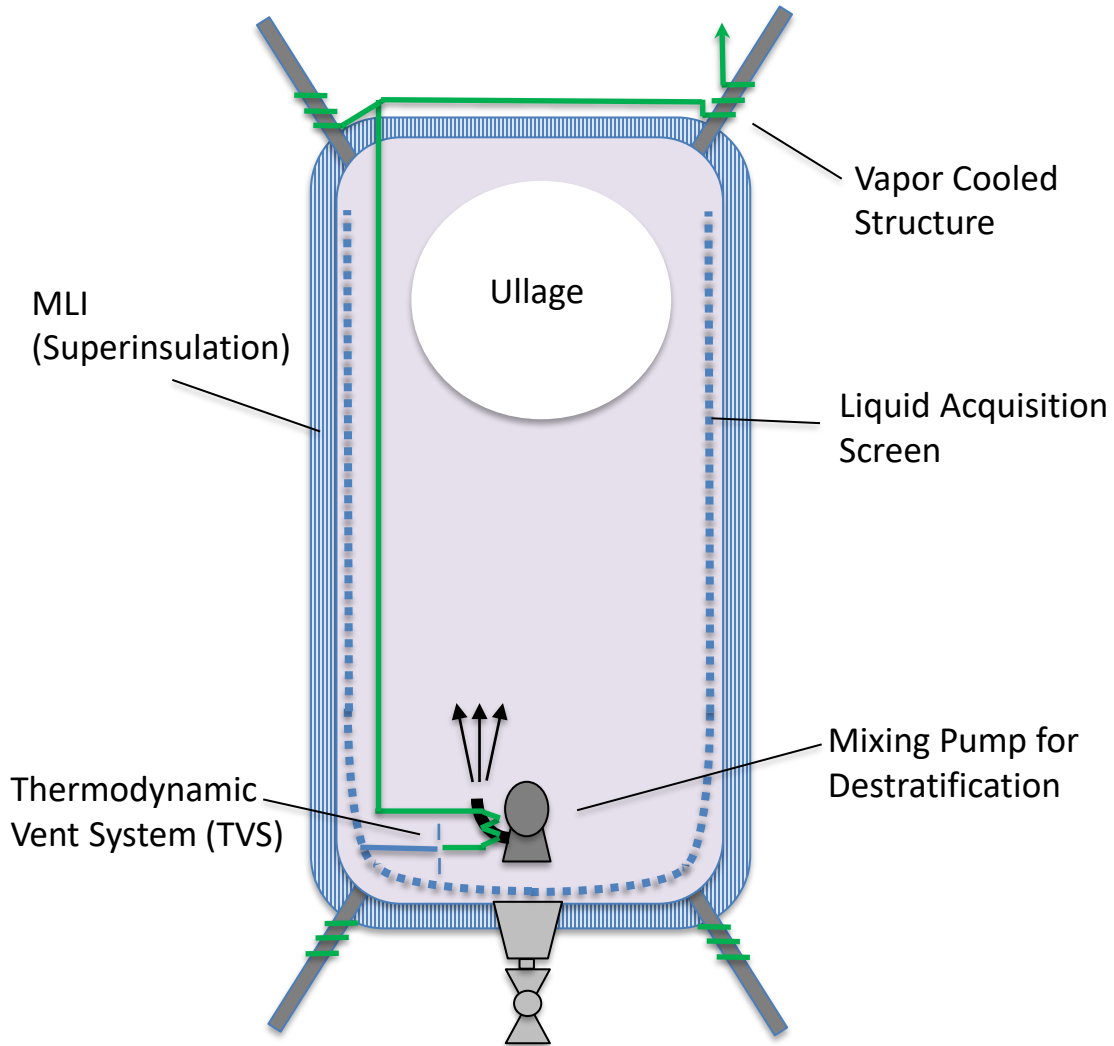
- Cryo-refrigeration heat intercept



Key Differences in the Advanced CFM Tank Thermal/Pressure Control Options



Modest Advancement $\longrightarrow$ Greatest Advancement



Basic Cryogenic Propellant Storage Approach Options



Option Number		Summary Description	Increasing Complexity ↓
1	Advanced Passive Thermal Control	Settled venting with mixing of the bulk liquid.	
2		Destratification mixing enhanced with <i>passive</i> cooling (i.e. TVS) and vapor cooling of structures.	
3		90 K Zero-Boil-Off (ZBO) system with dynamic mixing and <i>active</i> cooling (i.e. Cryocooler).	
4		Two-stage, 90 K (class) and 20 K (class ¹), Zero-Boil-Off (ZBO) storage system with dynamic mixing and <i>active</i> cooling (i.e. Cryocoolers).	

Application of Advanced CFM	SLS Upper Stage, EUS (LO2/LH2) (~5 days)	2024/2025 Lunar Mission (120-150 days)	Sustainable Lunar Missions (>120 days)	Mars Chemical Propulsion Transportation Vehicles and Landers (LO2/LCH4) >3 years	Mars Nuclear Thermal Propulsion (LH2 Storage for > 3 years)	In Situ Resource Utilization Cryogenic Propellant Production (Liquefaction of LO2)
Baseline Cryo Storage Solution ^{#1}	Option 1 or Option 2	Option 3 or Option 4	Option 3 or Option 4	Option 3	Option 4	Option 3

Challenges for In-Space Cryogenic Systems (Gaps in State of the Art)



We have limited demonstration of the capability to store cryogenic propellants in space for more than a few hours in microgravity

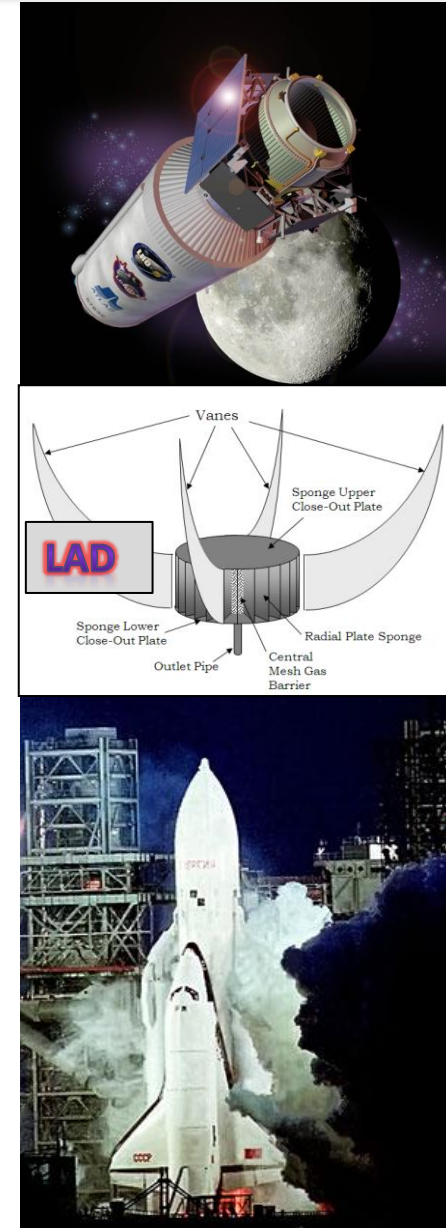
- SOA is Centaur's 9 hours with boil-off rates on the order of a few percent per day
- Large heat loads/mass-transfer rates partially mask effects of non-condensable in the ullage
- Operational systems require active mixing to encourage destratification and interface heat transfer for pressure control
 - Non-condensable gases can impede condensation affecting pressure control needed for long-duration ZBO storage in microgravity

We have not yet demonstrated that we can get gas-free liquid cryogenics out of a tank in microgravity

- Gas-free liquid is required for safe operation of a cryogenic propulsion system
- Need robust surface-tension **liquid acquisition device (LAD)**, analogous to SOA storable propellants
 - Non-condensable gas near the surface of screen type LADs is known to influence performance
- Only known experience in the world is the Russian Buran's single flight (liquid oxygen reaction control system)

We have not yet demonstrated the ability to move cryogenic liquids from one tank (or vehicle) to another in microgravity

- Non-condensable in the ullage complicates the required operations



ZBOT-1:

- ✓ Natural Convection
- ✓ Forced Mixing
- ✓ Microgravity Thermal Stratification
- ✓ Evaporation/Condensation
- ✓ Interfacial Phenomena & Turbulence Effects
- ✓ Free Surface Dynamics /Ullage Dynamic

ZBOT-NC:

- NCG Effect on Condensation/Evaporation
- Non-Condensable Gas Transport
- Double Diffusive Barriers
- Marangoni Convection
- Interfacial Mass Transfer Kinetics

ZBOT-DP:

- Droplet Breakup & Transport
- Droplet Phase Change
- Droplet-Ullage-Liquid Interaction
- Broad Area Cooling

ZBOT-FT:

- Flow & Pool Boiling Regimes/Transitions
- Wall Condensation, Film Formation & Spread
- Contact Angle Dynamics & Thin Film Evaporation

1g Large-Scale Cryogenic Experiments



K-Site, MHTB, SHIIVER

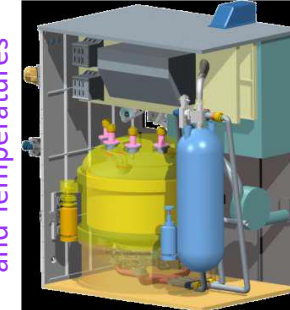
μ g-Science Experiments with Simulant Fluids



TCPE, ZBOT

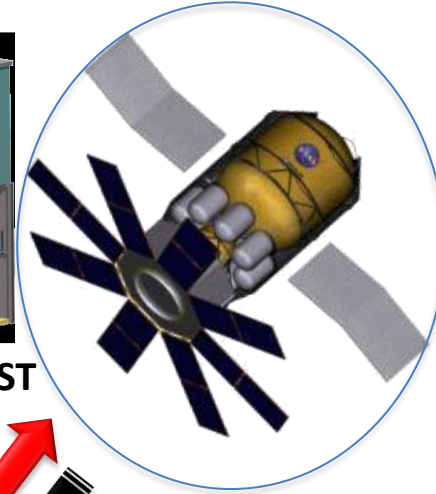
Detailed Measurements,
Fundamental Physics

μ g-Subscale Experiments with Cryogenics



RRM3, ICEE, FROST

μ g Cryo Large-Scale Demonstrations



Real Fluid Properties
and Temperatures

Experimentation

Modeling/Analysis

State-of-the-Art Models

New State-of-the-Art Multiphase Model Development and Validation

Integrated Full-Scale System Design

Transport & Phase Change Phenomena in a Cryogenic Storage Tank

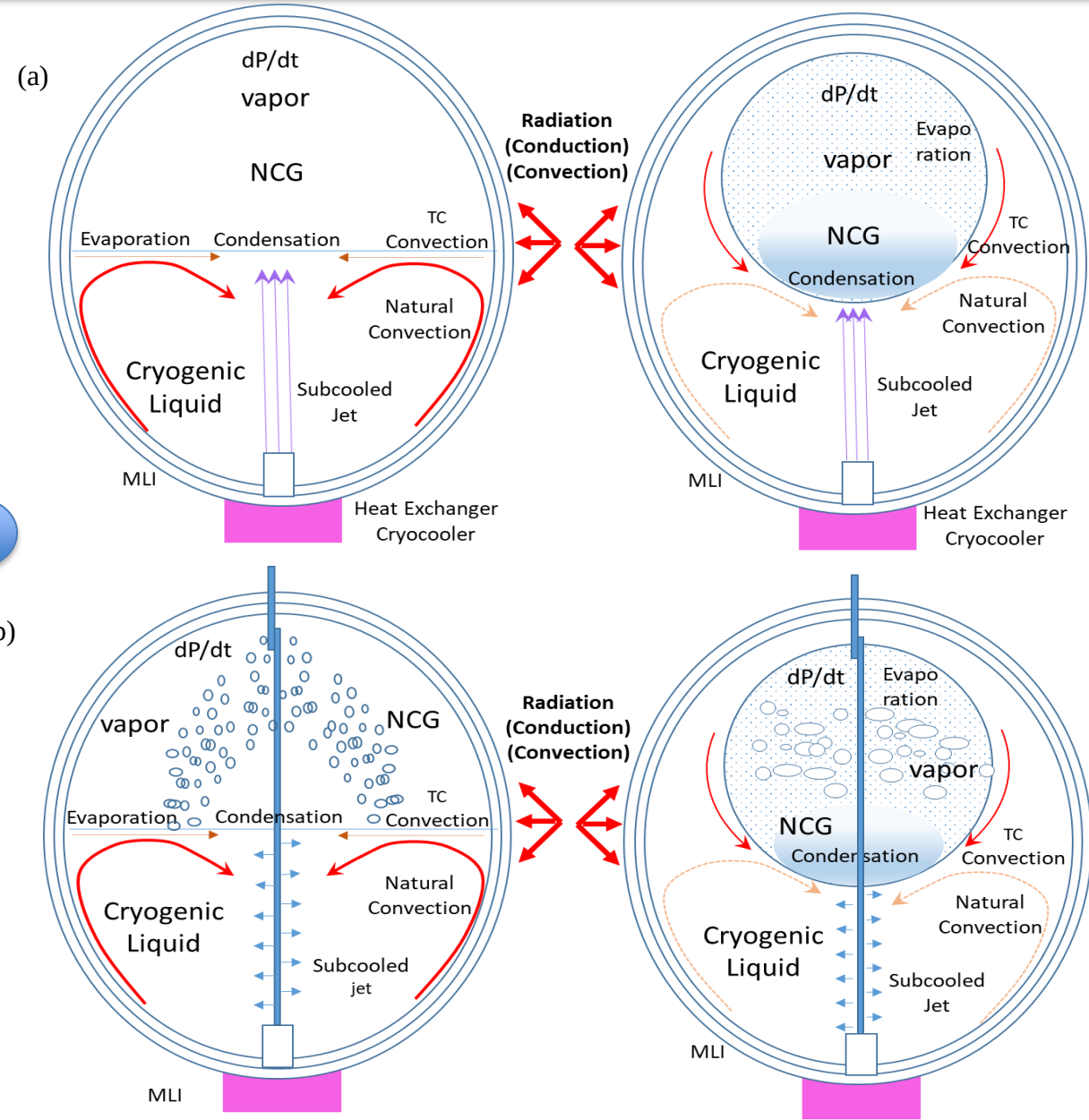
- ✓ Natural Convection
- ✓ Forced Mixing
- ✓ Microgravity Thermal Stratification
- ✓ Evaporation/Condensation
- ✓ μg Superheats/Nucleate Boiling
- ✓ Free Surface Dynamics /Ullage Dynamic
- NCG Effect on Condensation/Evaporation
- Non-Condensable Gas Transport
- Double Diffusive Barriers
- Marangoni Convection
- Interfacial Mass Transfer Kinetics
- Droplet Breakup & Transport
- Droplet Phase Change
- Droplet-Ullage-Liquid Interaction
- Wall Condensation Film Formation & Spread
- Contact Angle Dynamics & Thin Film Evaporation
- Heat Transfer Regimes/Transitions
- Sloshing/Interface Stability
- Phase Control/Positioning
- Interfacial Turbulence Effects

Experimentation

Modeling/Analysis

1G

0G



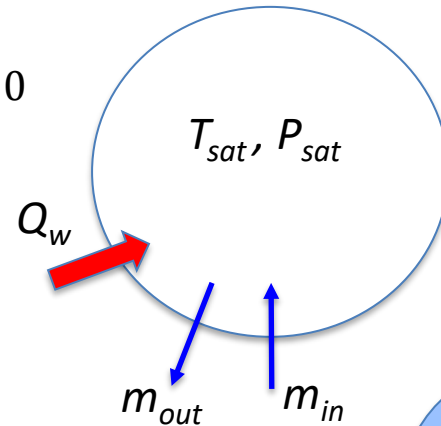
Thermodynamic Model for Storage Tank Self-Pressurization & Pressure Control

Mass Conservation:

$$\frac{d}{dt}(m_v + m_l) = \dot{m}_{outlet} - \dot{m}_{inlet} = 0$$

$$\dot{m}_{in} = \dot{m}_{out} = \dot{m}_{jet}$$

$$\frac{d}{dt}(\rho_v V_v) = -\frac{d}{dt}(\rho_l V_l) = \dot{M}$$



Energy Conservation:

$$\frac{d}{dt}(E_v) + \frac{d}{dt}(E_l)$$

$$= \dot{Q}_w + \frac{d}{dt}(E_{inlet}) - \frac{d}{dt}(E_{outlet}) + \dot{W}_{inlet} - \dot{W}_{outlet}$$

Pressure Work

$$\dot{W} = p v A$$

$$\frac{d}{dt}(m_v u_v) + \frac{d}{dt}(m_l u_l)$$

$$= \dot{Q}_w + \dot{m}_{inlet} u_{l,inlet} - \dot{m}_{outlet} u_{l,outlet} + p_{inlet} v_{l,inlet} A_{inlet} - p_{outlet} v_{l,outlet} A_{outlet}$$

Thermodynamics

$$p_l = p_v = p_{sat}$$

$$u = h - p / \rho$$

$$T_l = T_v = T_{sat}$$

$$h_v - h_l = L$$

$$T_{sat}^{n+1} = T_{sat}^n + \Delta t \left(\frac{dT_{sat}}{dt} \right)^n$$

$$\frac{dT_{sat}}{dt} = \frac{\dot{Q}_w + \dot{m}_{jet} c_{pl} (T_{jet} - T_{sat})}{L \frac{d(V_v \rho_v)}{dT_{sat}} + V_v \rho_v \frac{dh_v}{dT_{sat}} + V_l \rho_l \frac{dh_l}{dT_{sat}} - V_t \frac{dp_{sat}}{dT_{sat}}}$$

$$\frac{d\rho_l}{dT} = \beta \rho_l \quad \frac{d(V_v \rho_v)}{dT_{sat}} = V_v \frac{d(\rho_v)}{dT_{sat}} + \rho_v \left(\frac{d(V_v)}{d\rho_v} \frac{d\rho_v}{dT_{sat}} + \frac{d(V_v)}{d\rho_l} \frac{d\rho_l}{dT_{sat}} \right)$$

$$\frac{dh_v}{dT_v} = c_{p_v}$$

$$V_v = V_t \frac{\rho_{l_0} - \rho_l}{\rho_v - \rho_l} + V_{v_0} \frac{\rho_{v_0} - \rho_{l_0}}{\rho_v - \rho_l}$$

$$\frac{dh_l}{dT_l} = c_{p_l}$$

$$\frac{d\rho_v}{dT_{sat}} = \frac{1}{RT_{sat}} \frac{dp_{sat}}{dT_{sat}} - \frac{p_{sat}}{R} T_{sat}^{-2}$$

$$\frac{dp_{sat}}{dT_{sat}} = p_B e^{\frac{L}{R} \left(\frac{1}{T_B} - \frac{1}{T_{sat}} \right)} \left(\frac{L}{R} T_{sat}^{-2} \right)$$

$$\frac{d(V_v)}{d\rho_v} = \frac{V_v}{\rho_l - \rho_v}$$

$$\rho_v = \frac{p_{sat}}{RT_{sat}}$$

$$\frac{d(V_v)}{d\rho_l} = \frac{V_t - V_v}{\rho_l - \rho_v}$$

$$V_l = V_t - V_v$$

Zonal (Multi-node) Model for Storage Tank Self-Pressurization & Pressure Control

Mass Conservation:

$$\frac{dm_l}{dt} = -\dot{M}_i + \dot{m}_{inlet} - \dot{m}_{outlet}$$

$$\frac{dm_v}{dt} = \dot{M}_i$$

Energy Conservation:

$$\begin{aligned} \frac{d}{dt}(m_l u_l) &= \dot{Q}_{wl} - \dot{M}_i u_i + \dot{Q}_{il} + \dot{m}_{inlet} u_{inlet} - \dot{m}_{outlet} u_{outlet} \\ &\quad + \dot{W}_{inlet} - \dot{W}_{outlet} - \dot{W}_{iflow} - \dot{W}_{iboundary} \\ \frac{d}{dt}(m_v u_v) &= \dot{Q}_{wv} + \dot{M}_i u_i - \dot{Q}_{iv} + \dot{W}_{iflow} - \dot{W}_{iboundary} \end{aligned}$$

Pressure Work

$$\dot{W} = p v A$$

$$\dot{W} = p_v \frac{dV_l}{dt}$$

$$\dot{W} = p_v \frac{dV_v}{dt}$$

$$\rho u = \rho h - p$$

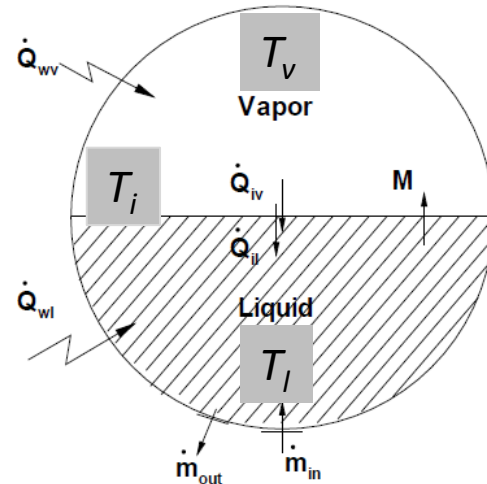
$$h_v = h_{v_0} + c_{pv}(T_v - T_{v_0})$$

$$h_l = h_{l_0} + c_{pl}(T_l - T_{l_0})$$

Thermodynamics

$$\frac{dh_v}{dT_v} = c_{pv}$$

$$\frac{dh_l}{dT_l} = c_{pl}$$



$$\begin{aligned} V_l \rho_l c_{pl} \frac{dT_l}{dt} - V_l \frac{dp_v}{dt} &= \dot{Q}_{wl} + \dot{M}_i c_{pl}(T_l - T_i) + \dot{Q}_{il} + \dot{m}_{jet} c_{pl}(T_{inlet} - T_l) \\ V_v \rho_v c_{pv} \frac{dT_v}{dt} - V_v \frac{dp_v}{dt} &= \dot{Q}_{wv} + \dot{M}_i c_{pv}(T_i - T_v) - \dot{Q}_{iv} \end{aligned}$$

$$\dot{M}_i = -\frac{\dot{Q}_{il} - \dot{Q}_{iv}}{h_{i_v} - h_{i_l}} \quad h_{i_v} - h_{i_l} = L$$

$$\dot{M}_i = \frac{2\sigma}{2 - \sigma} A_i \left(\frac{M_w}{2\pi R T_i} \right)^{1/2} (p_v - p_{sat}) \quad A_i = \pi r_t^2$$

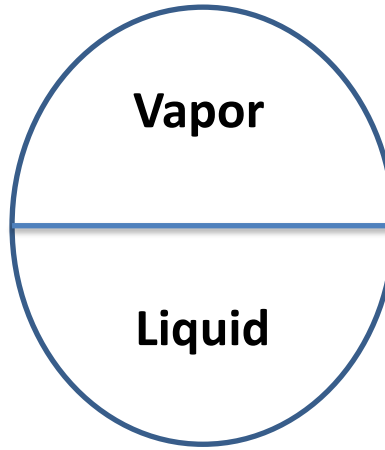
$$\frac{\dot{Q}_{il} - \dot{Q}_{iv}}{L} = \frac{2\sigma}{2 - \sigma} A_i \left(\frac{M_w}{2\pi R T_i} \right)^{1/2} (p_{sat} - p_v)$$

$$\dot{Q}_{il} = h_{c_{il}} A_i (T_i - T_l) \quad h_{c_{il}} = \frac{k_l Nu_l}{r_t}$$

$$Nu = 0.12 Ra^{1/3} \quad Ra = \frac{\rho^2 c_p g \beta (T_{avr} - T_{bulk} L_c^3)}{\mu k}$$

Two-Phase **Sharp Interface** Storage Tank CFD Model

Equation	Liquid	Ullage
Continuity	✓	✓
Navier Stokes	✓	✓
Energy	✓	✓
Species	✓	✓
Turbulence	✓	✓



$$P_v = \frac{\omega_v M_g}{\omega_v M_g + (1 - \omega_v) M_v} P \quad \checkmark$$

Interfacial Energy Balance:

$$T_I = T_{sat}(P_v) \quad \checkmark$$

$$LJ_v = -k_l \vec{\nabla} T_l \cdot \hat{n} + k \cdot \vec{\nabla} T \cdot \hat{n} \quad \checkmark$$

Schrage Interfacial Mass Transfer:

$$J_v = \frac{2\sigma}{2 - \sigma} \frac{1}{\sqrt{2\pi R T_I}} [P_{sat}(T_I) - P_v] \quad \checkmark$$

$$\frac{P_{sat}(T_I)}{P_r} = e^{\left[\frac{L}{R} \left(\frac{1}{T_r} - \frac{1}{T_I}\right)\right]} \quad \checkmark$$

Stefan Wind:

$$J_v = - \left(\frac{\rho D_m}{1 - \omega_v} \right) \nabla \omega \cdot \hat{n} \Big|_I$$

Continuity: $\frac{\partial \rho}{\partial t} + \nabla(\rho \mathbf{v}) = S_c$

Momentum: $\frac{\partial}{\partial t}(\rho \mathbf{v}) + \nabla(\rho \mathbf{v} \mathbf{v}) = -\nabla p + \nabla[\mu_{eff}(\nabla \mathbf{v} + \nabla \mathbf{v}^T)] + \rho \mathbf{g} + \mathbf{F}_M$

Energy: $\frac{\partial}{\partial t}(\rho E) + \nabla(\mathbf{v}(\rho E + p)) = \nabla(k_{eff} \nabla T) + S_E$

Species: $\frac{\partial}{\partial t}(\rho \omega) + \nabla(\vec{v}(\rho \omega)) = \nabla \cdot (\rho D_m \nabla \omega) + S_\omega$

Two-Phase VOF Interface Storage Tank CFD Model

Energy and Temperature as mass average scalars:

$$E = \frac{\sum_{q=1}^2 \alpha_q \rho_q E_q}{\sum_{q=1}^2 \alpha_q \rho_q}$$

Properties:

$$\rho = \sum_{q=1}^2 \alpha_q \rho_q, \quad \mu_{eff} = \sum_{q=1}^2 \alpha_q \mu_{eff\ q}, \quad k_{eff} = \sum_{q=1}^2 \alpha_q k_{eff\ q}$$

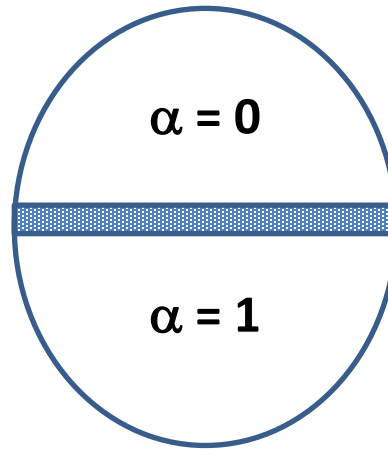
Continuity of Volume Fraction of the q -th phase:

$$\frac{1}{\rho_q} \left[\frac{\partial}{\partial t} (\alpha_q \rho_q) + \nabla \cdot (\alpha_q \rho_q \vec{v}_q) \right] = S_{\alpha_q}$$

Continuum Surface Force (Brackbill et al.):

$$\mathbf{F}_M = \sum_{pairs\ ij, i < j} \sigma_{ij} \frac{\alpha_i \rho_i h_i \nabla \alpha_j + \alpha_j \rho_j h_j \nabla \alpha_i}{\frac{1}{2} (\rho_i + \rho_j)}$$

where $h_i = \nabla \cdot \hat{n}$



Interfacial mass transfer per unit volume:

$$S_c = S_{\alpha_q} = \dot{\mathbf{m}}_i \cdot \mathbf{A}_i$$

$$\mathbf{A}_i = |\nabla \alpha|,$$

$\dot{\mathbf{m}}_i$ is a mass flux vector in kg/(m²·sec)

Schrage Interfacial Mass Transfer:

$$|\dot{\mathbf{m}}| = J = \left(\frac{2\sigma}{2 - \sigma} \right) \left(\frac{M}{2\pi R} \right)^{1/2} \left(\frac{P_i}{T_i^{1/2}} - \frac{P_v}{T_i^{1/2}} \right)$$

Other recent approaches to VOF Interfacial Heat & Mass Transfer:

- VOF Tsat Interface Model: (Konopka, AIAA JTP&HT, 2019)

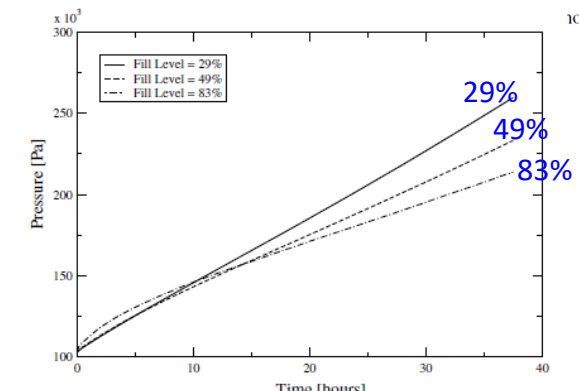
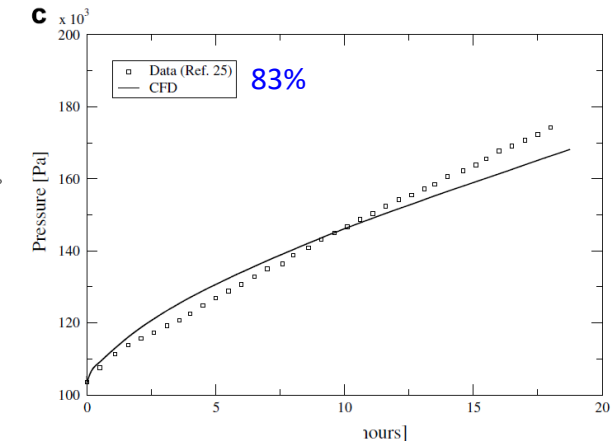
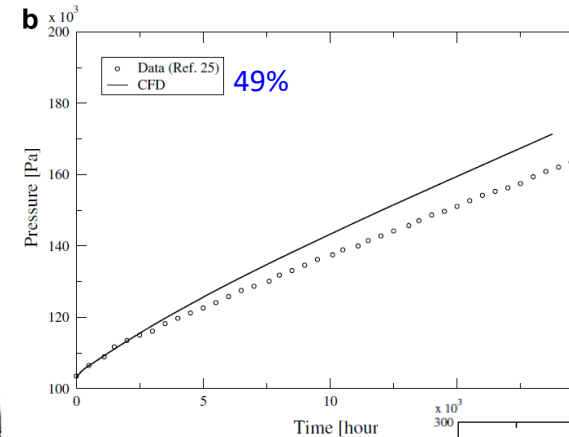
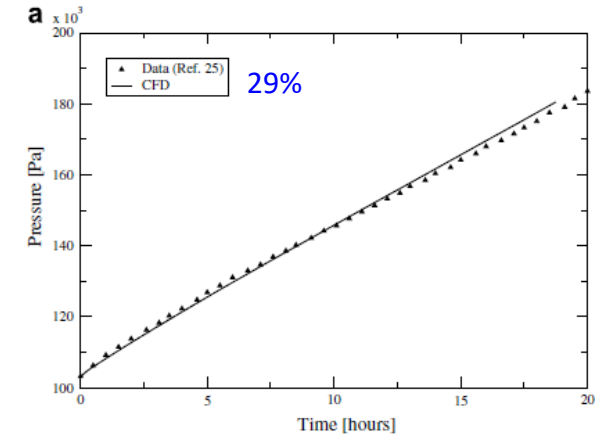
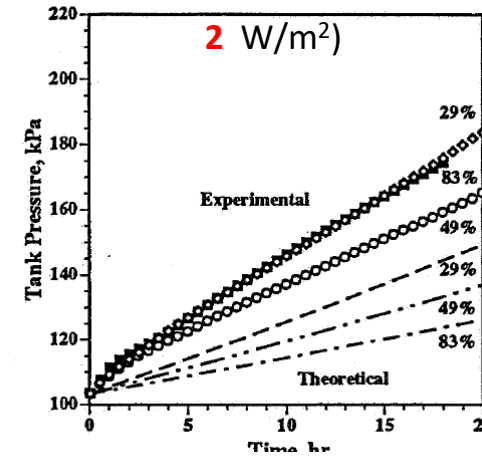
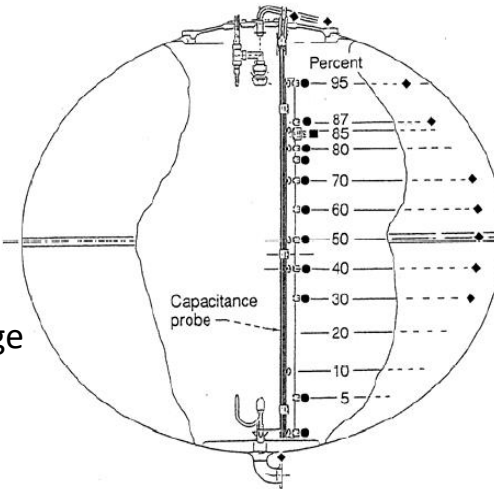
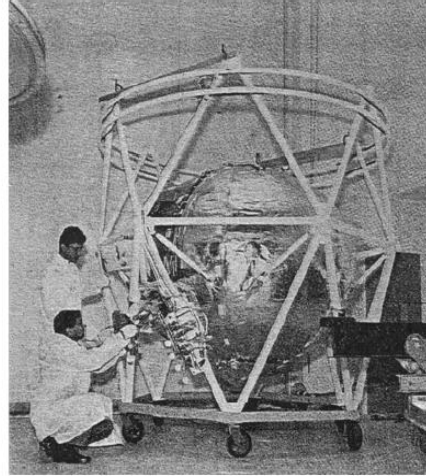


Propellant Tank Self-Pressurization:
Ground-Based Experiments and Model Simulation Studies of

Self-Pressurization Experiments at K-site Facility (1990-91)

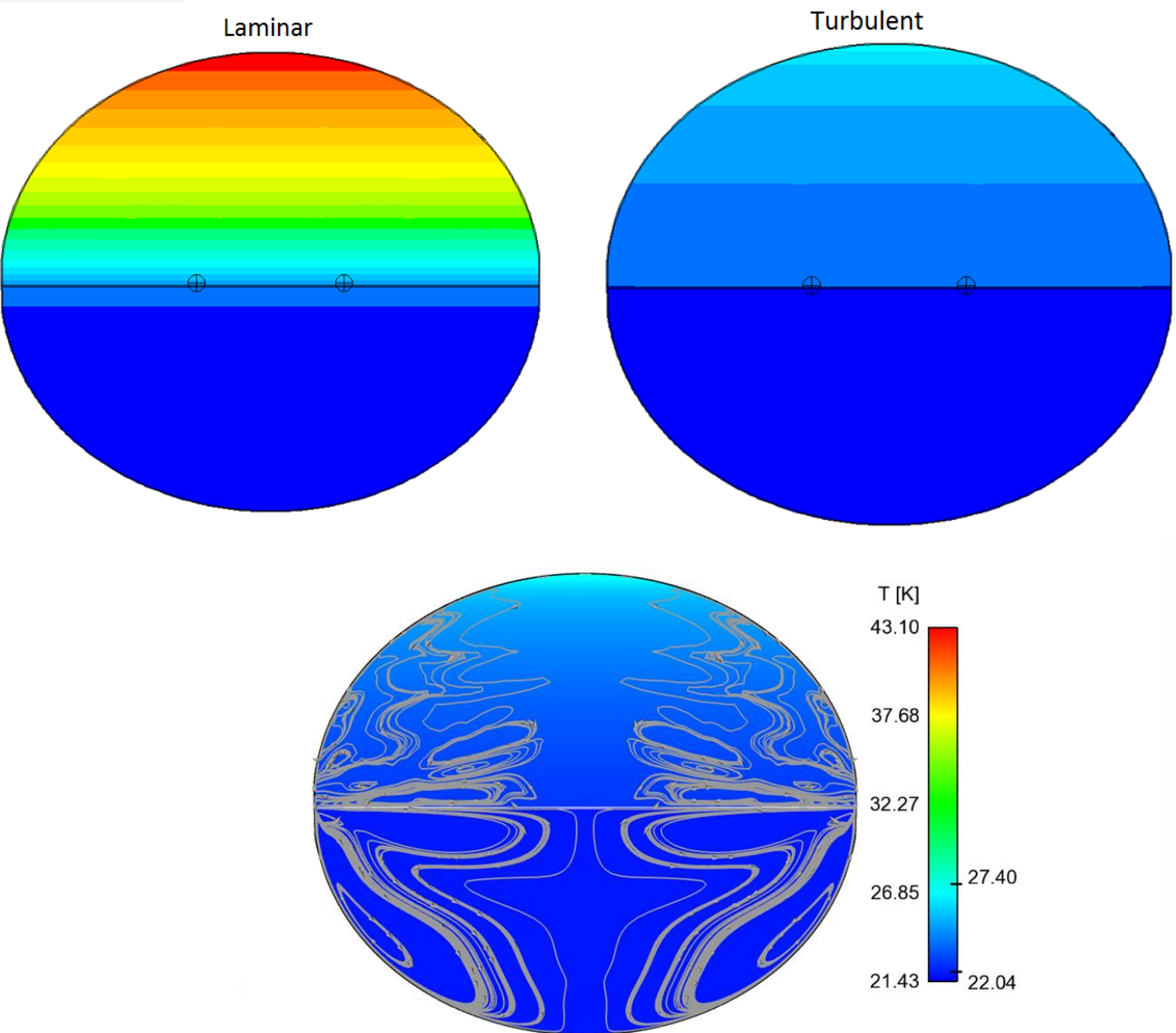


1. Flightweight insulated 2219-T62 aluminum ellipsoidal tank
 - Internal volume: $4.95 \text{ m}^3 = 175 \text{ ft}^3$
 - Tests conducted in vacuum chamber.
 - Test article is enclosed by a cryoshroud whose temperatures are maintained with electrical heaters.
 - Tank is insulated with 2 blankets of MLI.
2. Test fluid is liquid hydrogen
3. Steady **boil-off test** and measurement performed at 95% liquid fill fraction and 117 kPa (or 1.17 bar) tank pressure.
4. Tank fill level was reduced to desired fill level (29%, **49%**, 83%)
5. Self-pressurization tests were initiated from a stationary stratified state.
6. Two Cryoshroud Temps $\rightarrow$ Two heat loads (**2** & **3.5** W/m^2)
7. Grashof Number (Gr) based on 3.5 W/m^2 average heat flux into tank $\rightarrow$ **vapor: $\text{Gr} = 2.21\text{e}+13$; liquid: $\text{Gr} = 1.33\text{e}+14$** (which corresponds to turbulent natural convection for a steady-state natural convection flow)

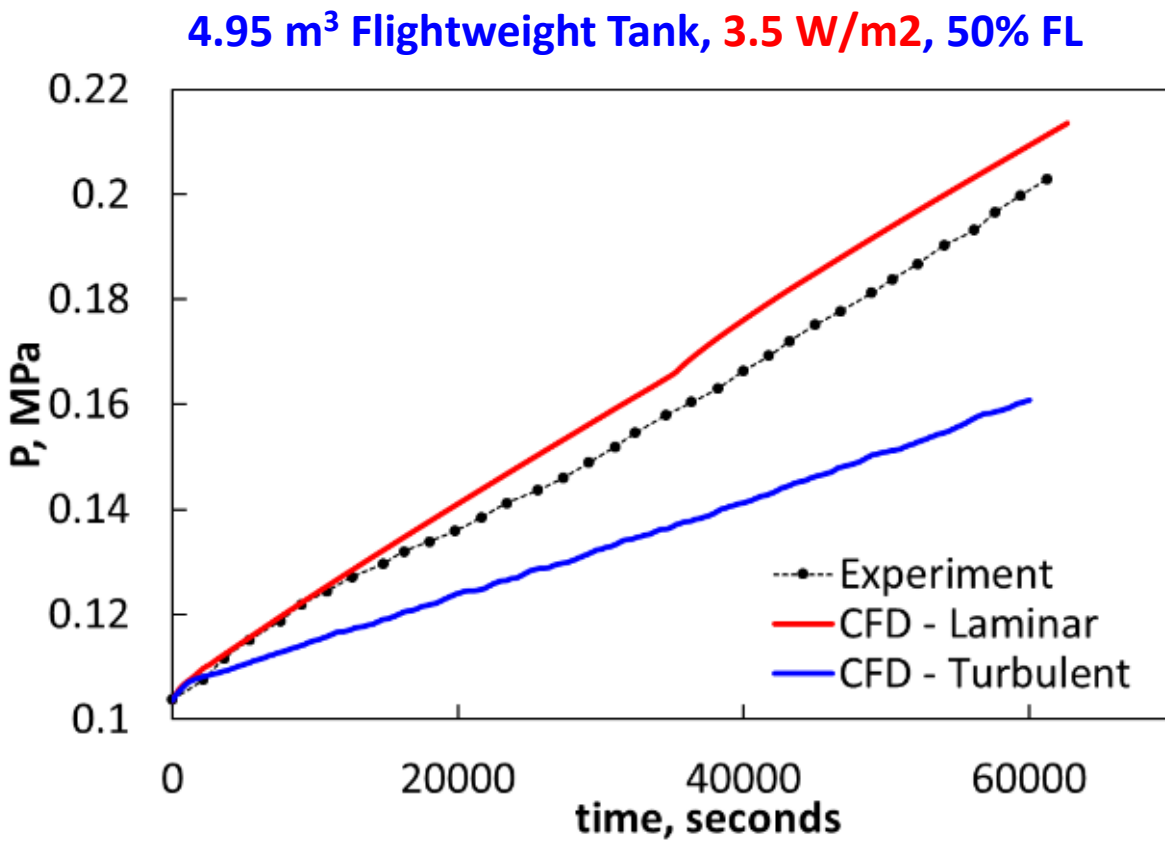




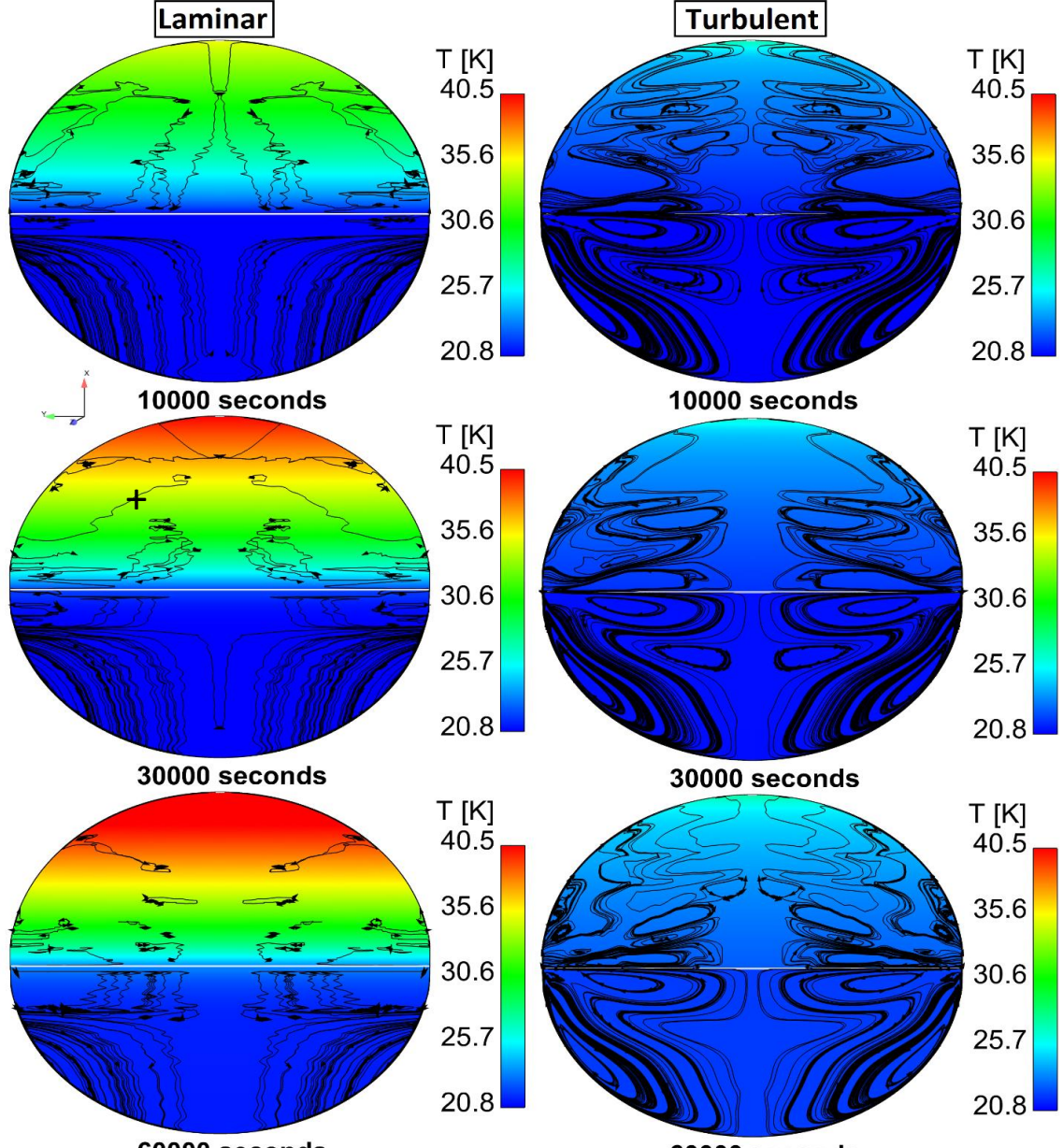
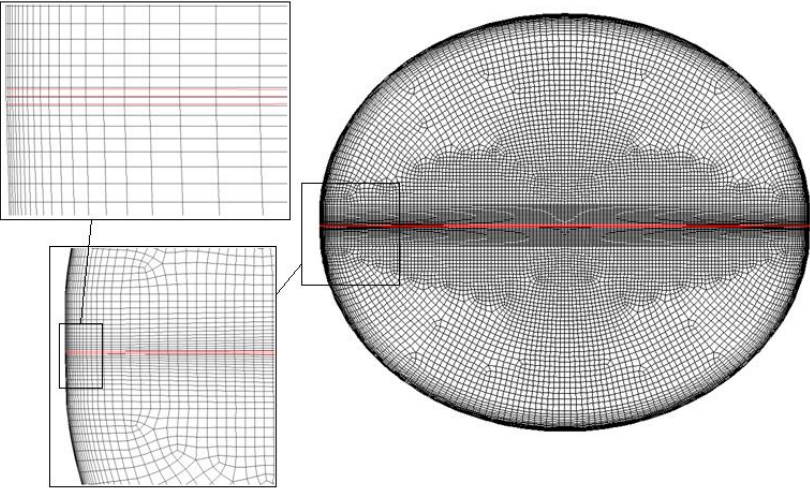
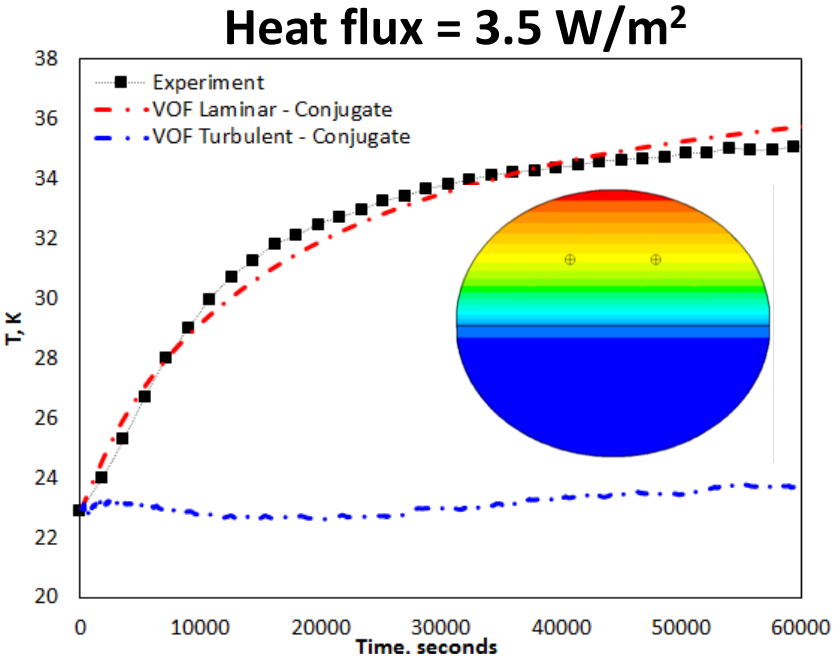
Self-Pressurization Experiments in the GRC K-site Facility (1990-91)



60,000 seconds of self-pressurization



K-Site LH2 Self-Pressurization: CFD Results –Temperature and Flow Field



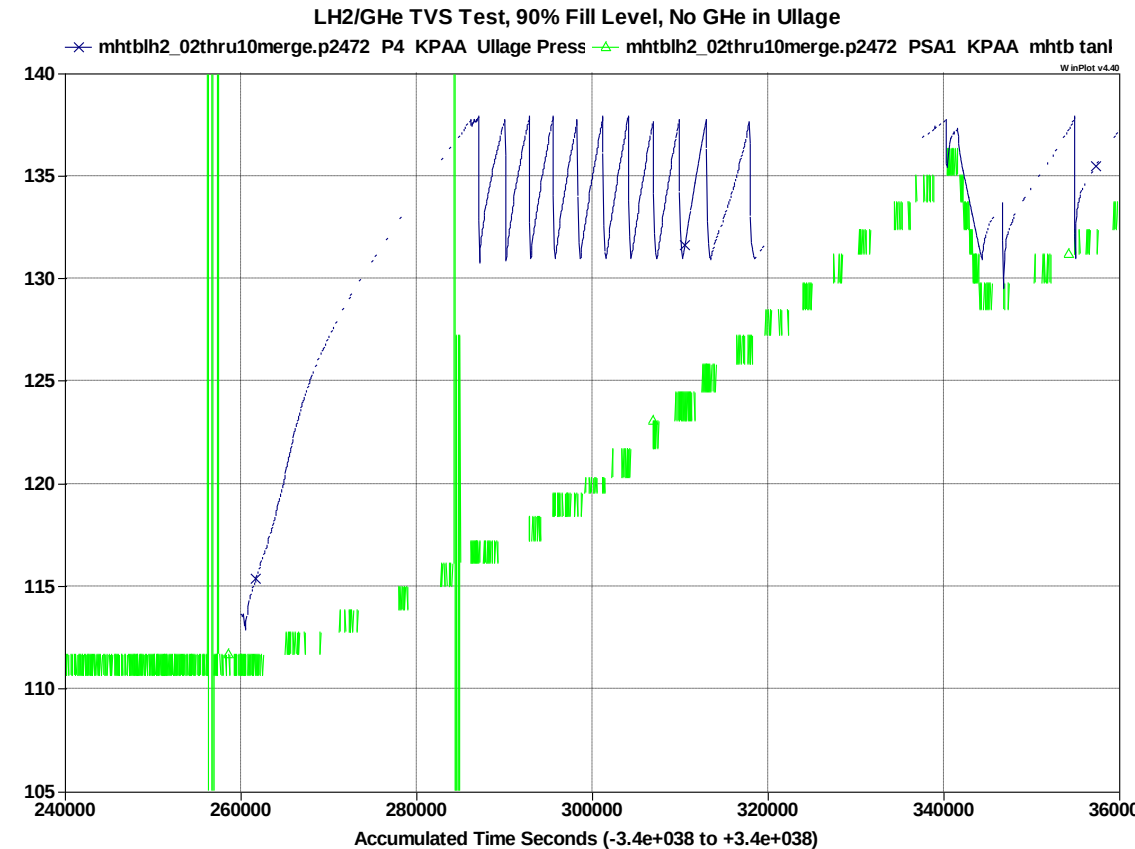
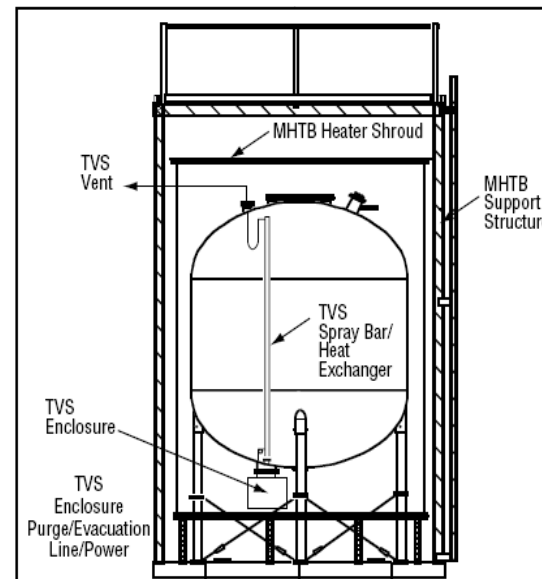
Self-Pressurization Experiments in the MSFC MHTB: the Multi-Purpose Hydrogen Testbed Facility (2000)



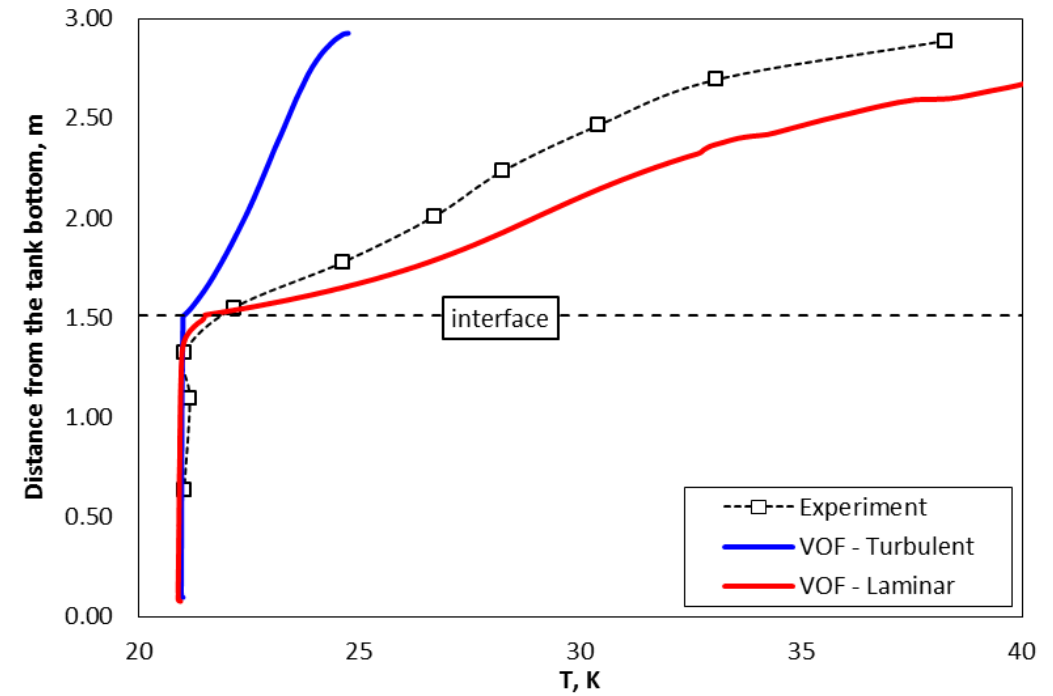
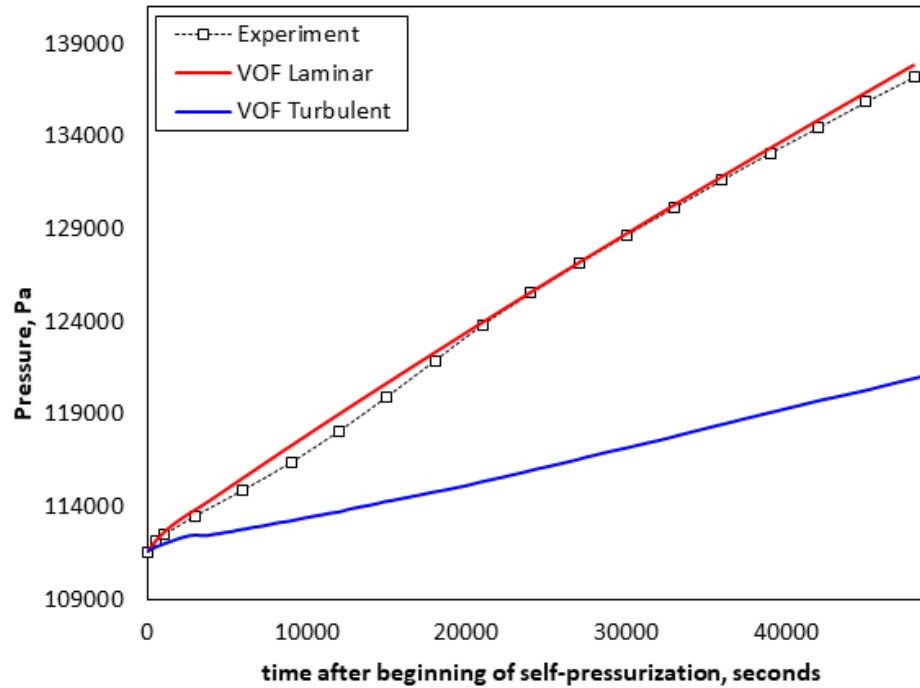
- Tank Internal volume 37.5 m^3
 - ❖ Cylindrical midsection with:
 - height = 3.05 m
 - diameter = 3.05 m
 - ❖ 2:1 elliptical top and bottom domes
- Tank is enclosed in a vacuum shroud
- Self-pressurization tests were run with LH2, LN2, LCH4 (with and without helium in the ullage)
- Boil-off test was performed prior to tank lockup and self-pressurization
- Most tests include 20, 50, 90% fill levels
- In the 50% fill ratio case, **a uniform heat flux of 0.89873 W/m^2 was applied at the wall in the vapor region, and 2.0841 W/m^2 in the liquid region.**
- 4 spray bar tubes attached to center tube heat exchanger



MHTB

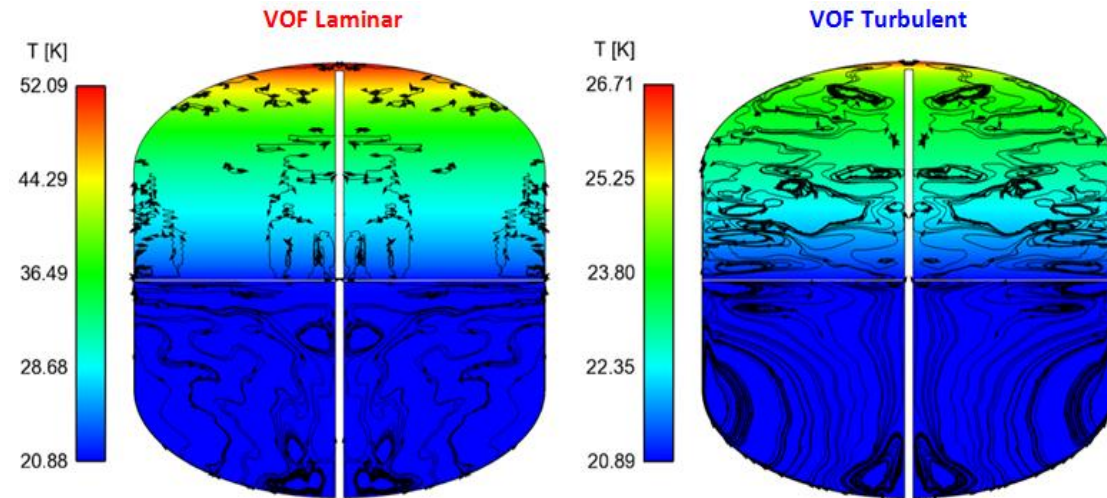


Self-Pressurization Experiments in the MSFC MHTB: the Multi-Purpose Hydrogen Testbed Facility (2000)



Tank Walls: Uniform heat flux:

- 15.35 W (0.89873 W/m^2) – vapor
- 35.65 W (2.0841 W/m^2) - liquid



Self-Pressurization Experiments in the GRC SHIVER: The Structural Heat Intercept, Insulation, and Vibration Evaluation Rig (2019)



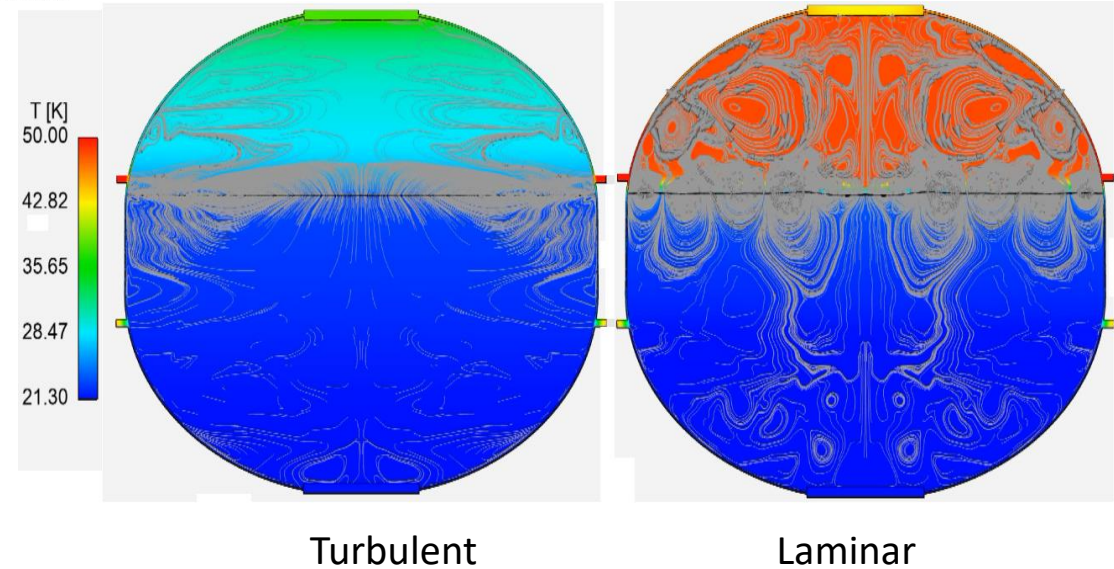
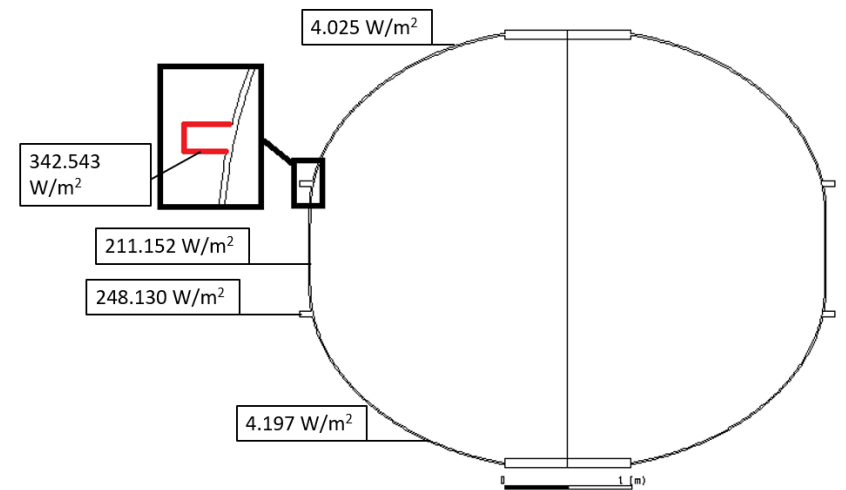
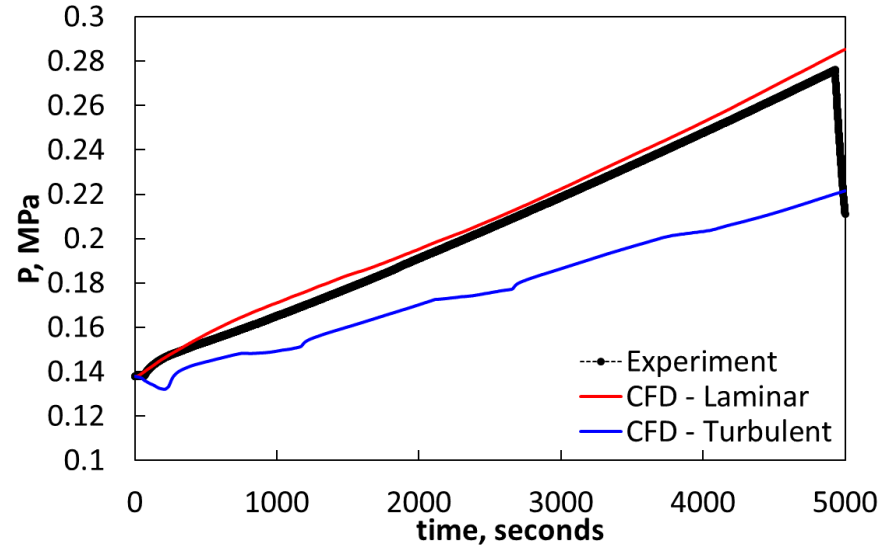
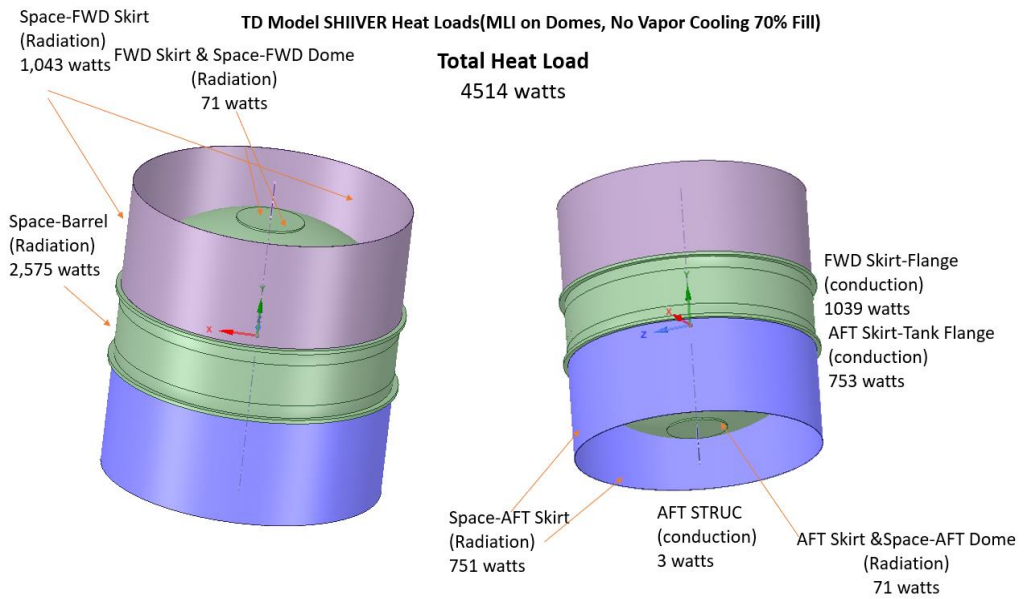
Forward Skirt
w/ cooling
loops

Tank

- 4 m Diam.
- 3.5 m Tall

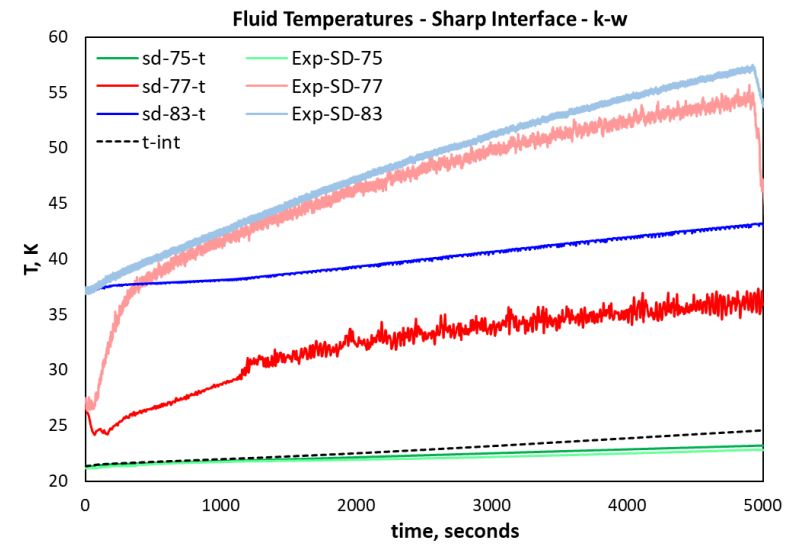
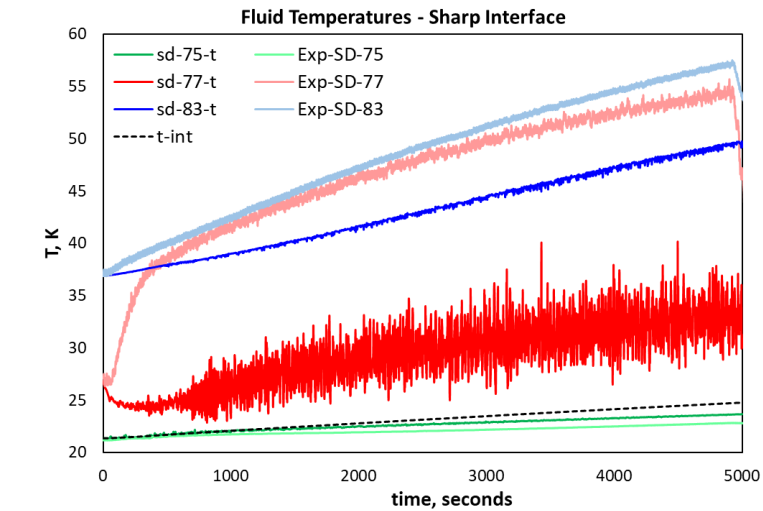
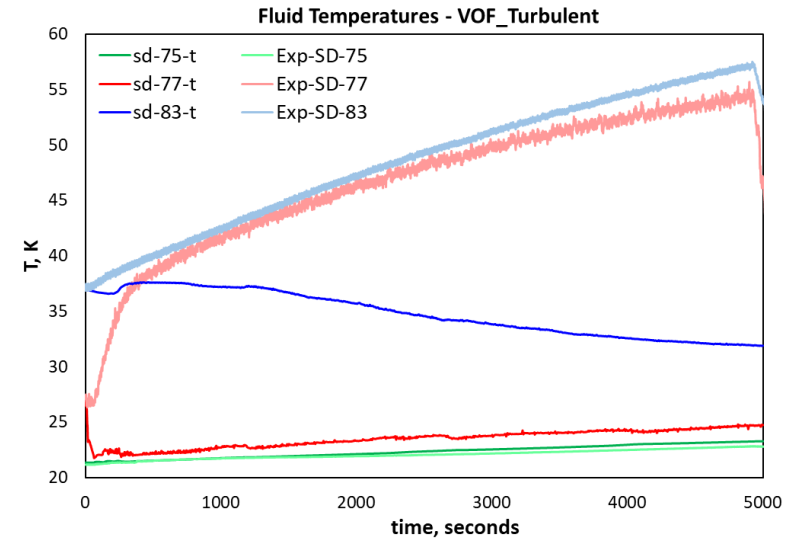
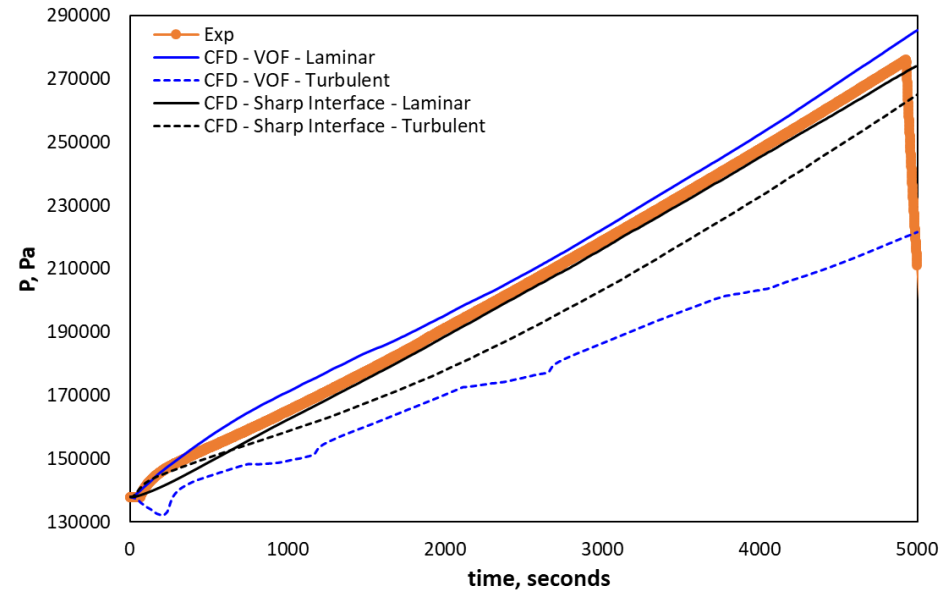
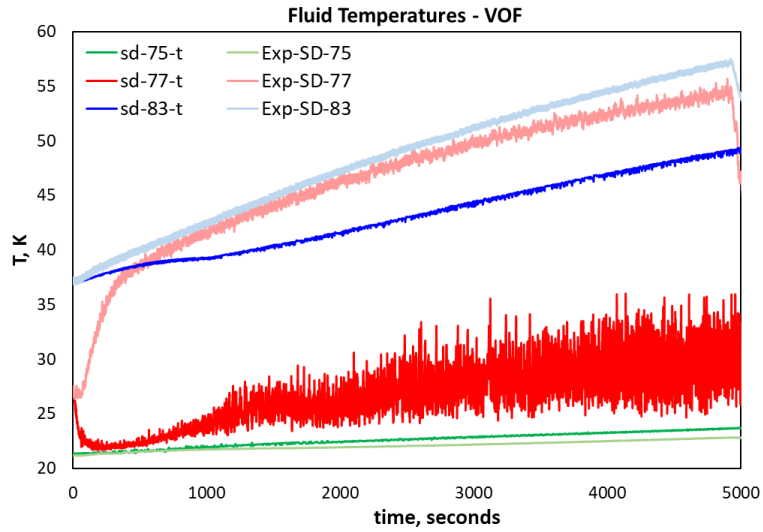
Aft Skirt

B2 Support
Structure





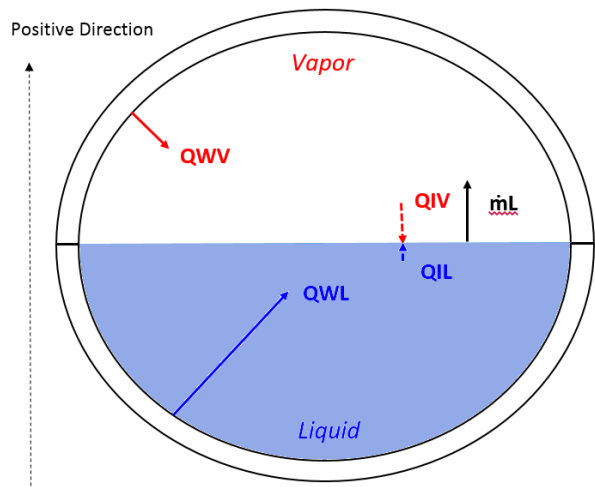
Shiiver Temperature Predictions – VOF vs Sharp-Interface - laminar vs. turbulent



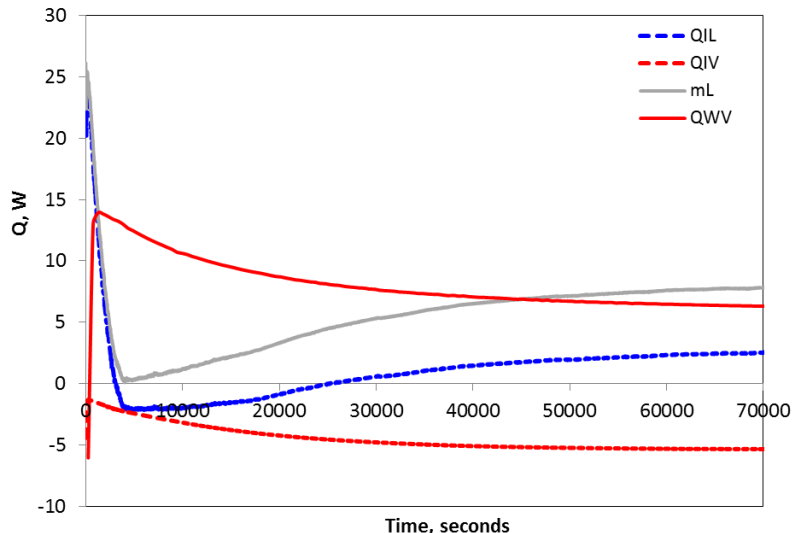
K-Site LH2 1G Self-Pressurization: Prediction of Heat Flow & Energy Distributions



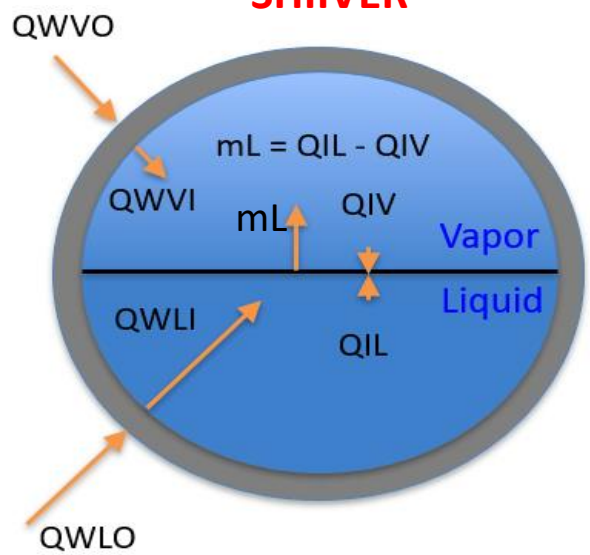
K-Site



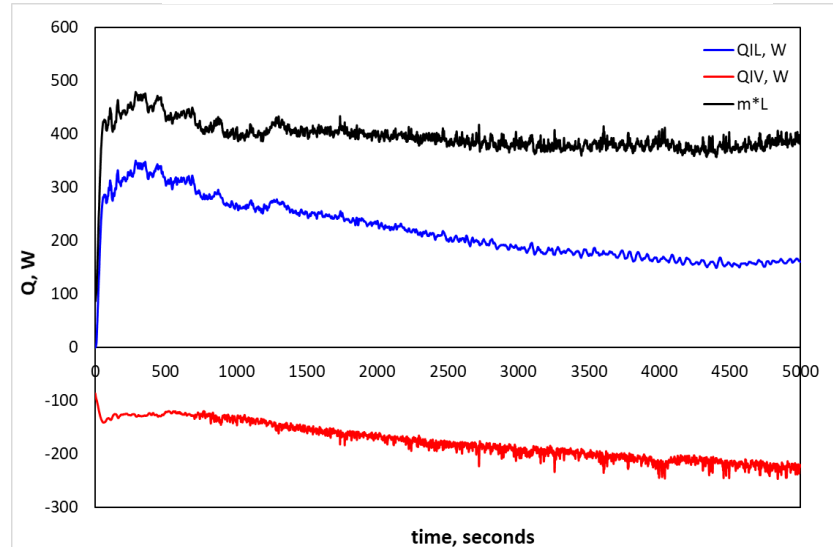
Heat Flows & Energy Distributions



SHIIVER



Heat Flows & Energy Distributions



$$\dot{m}L = Q_{IL} - Q_{IV}$$

$$\dot{m}L = -k_{l,eff} \vec{\nabla} T_l \cdot \hat{n} - k_{v,eff} \vec{\nabla} T_v \cdot \hat{n}$$
$$\dot{m} = \left(\frac{2\alpha}{2-\alpha} \right) \left(\frac{1}{\sqrt{2\pi R T_l}} \right) [P_{sat}(T_l) - P_v]$$

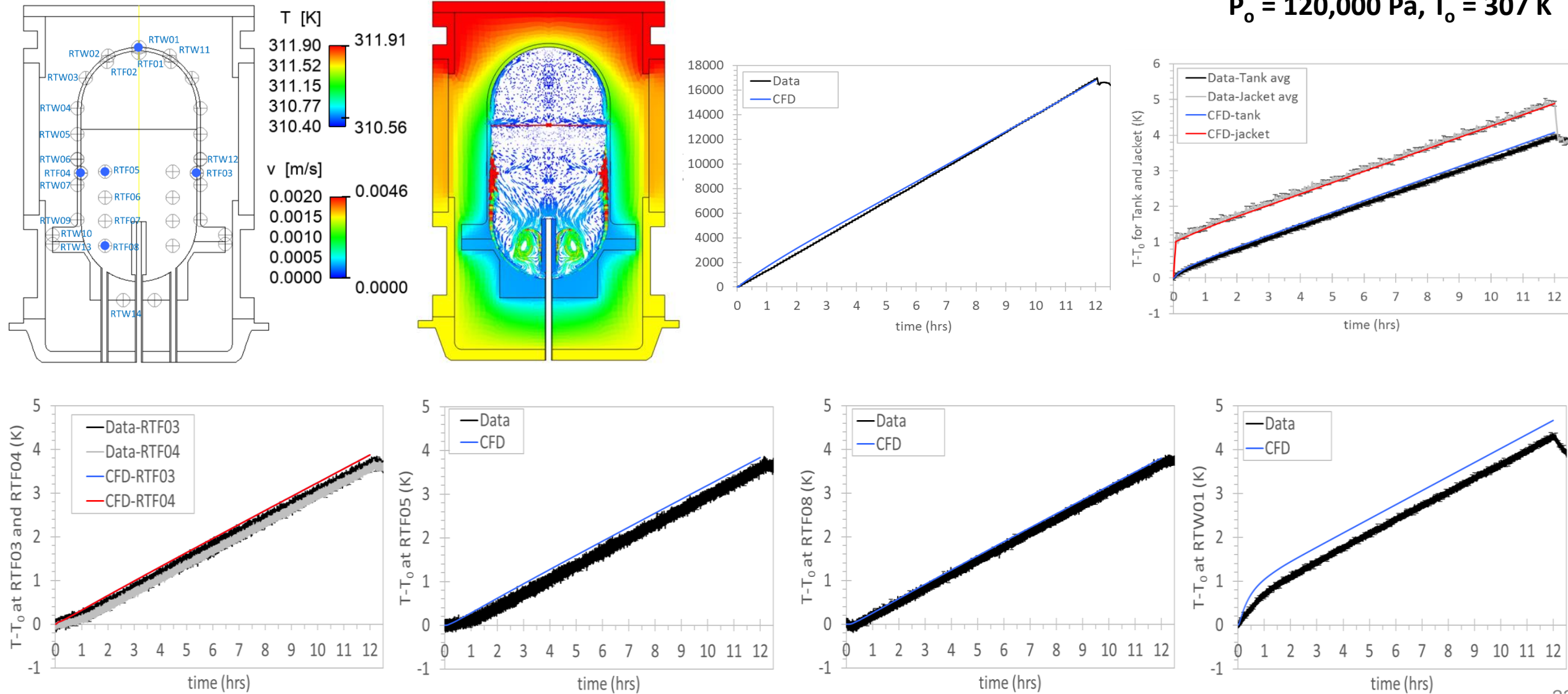
Exp.	Gr	Ra
K-Site	Liquid = 4.4e+14 Vapor = 9.7e+13	Liquid = 5.4e+14 Vapor = 7.7e+13
MHTB	Liquid = 9.0e+14 Vapor = 1.4e+14	Liquid = 1.1e+15 Vapor = 1.1e+14
SHIIVER	Liquid = 3.3e+15 Vapor = 1.4e+15	Liquid = 4.0e+15 Vapor = 1.1e+15

Ground Based Model Validation Experiment in Flight Hardware: 1G Self-Pressurization - Vacuum Jacket Heating



VJ Heating, $T_j = T_w + 1$ (3.75 W/m²), 70%, Self-Pressurization: $\{ Ra_L \rightarrow (10)^{10}, Ra_v \rightarrow (10)^7, Bo \rightarrow (10)^4 \}$

$P_o = 120,000$ Pa, $T_o = 307$ K

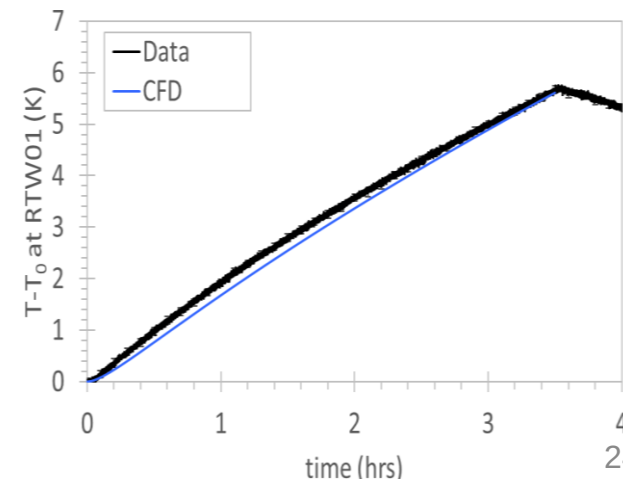
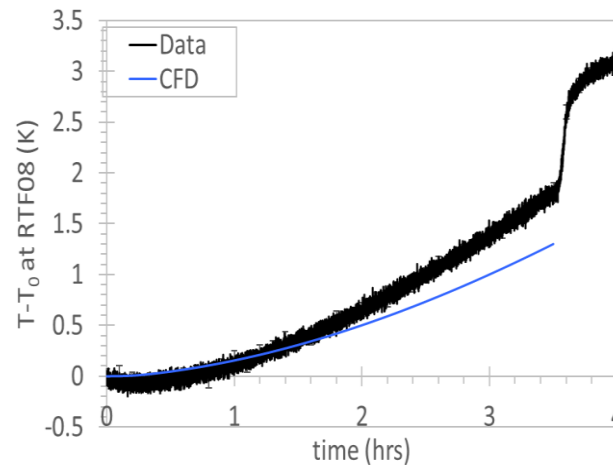
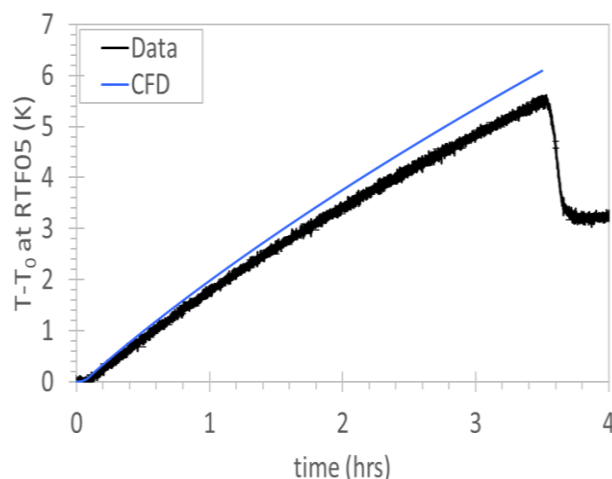
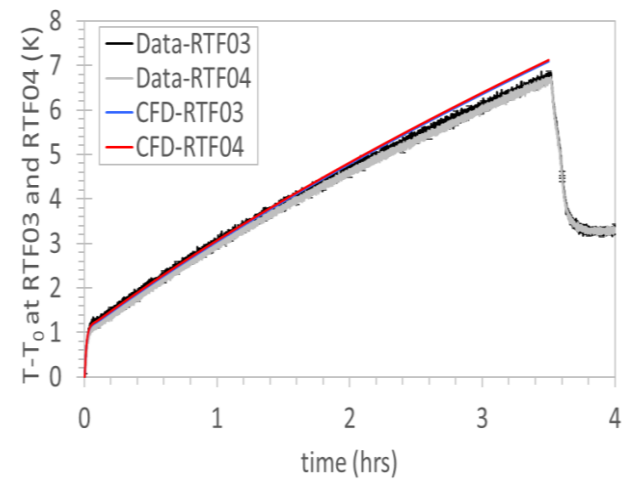
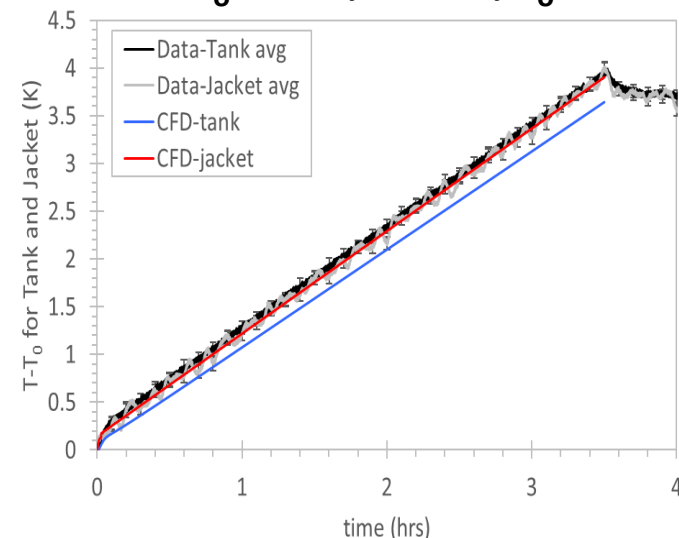
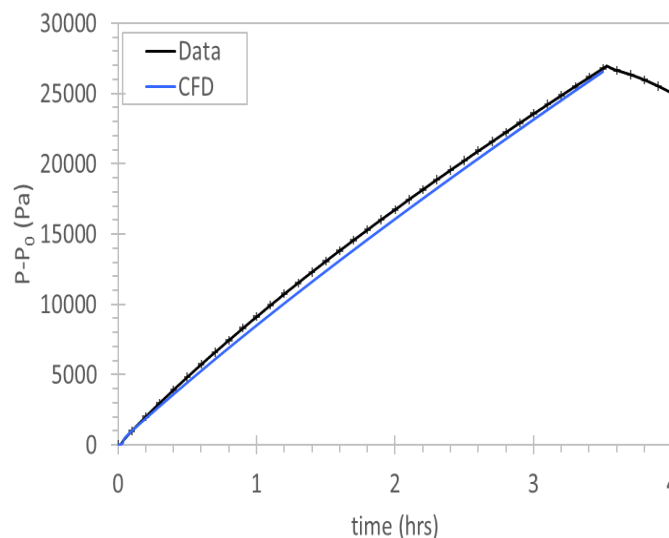
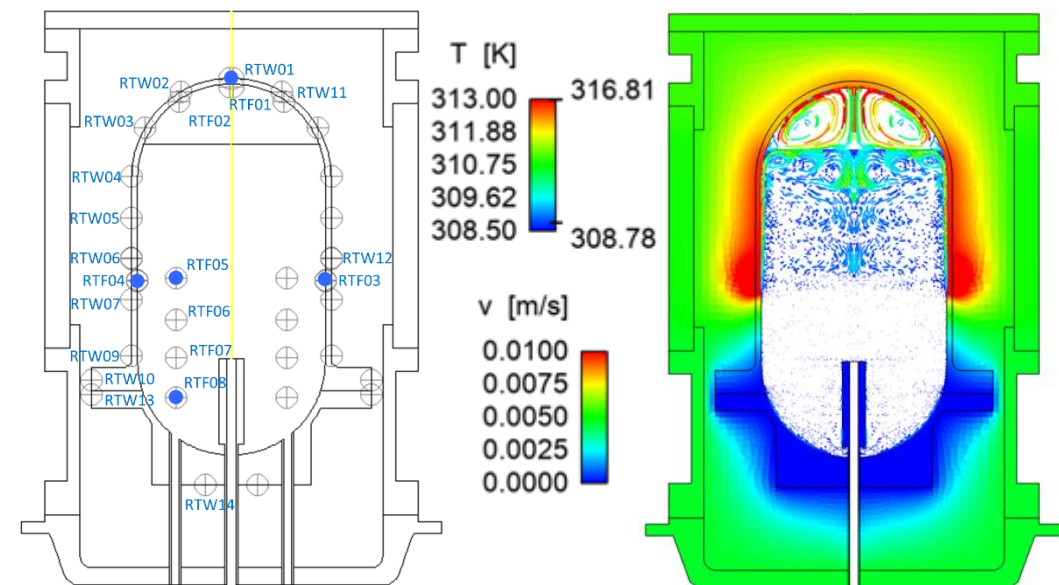


Ground Based Model Validation Experiment in Flight Hardware: 1G Self-Pressurization – Strip Band Heating



Strip Band Heating, 1W , 90%, Self-Pressurization: { $Ra_L \rightarrow (10)^{10}$, $Ra_v \rightarrow (10)^7$, $Bo \rightarrow (10)^4$ }

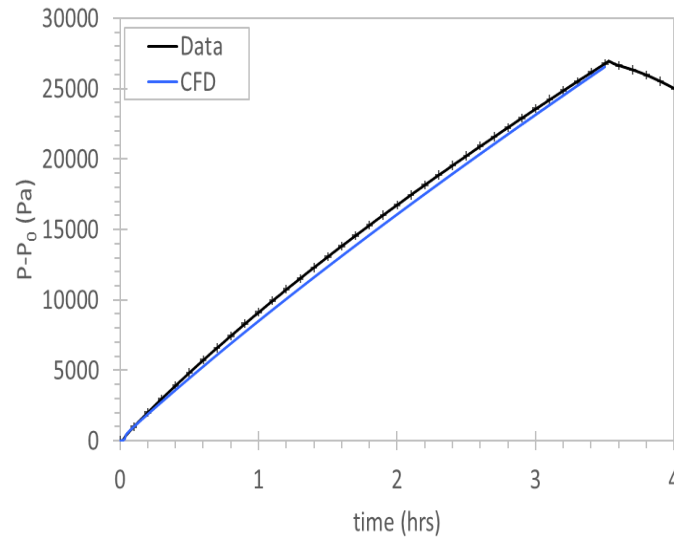
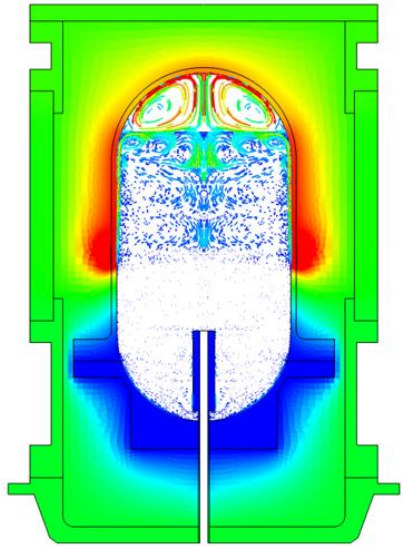
$P_o = 120,000 \text{ Pa}$, $T_o = 307 \text{ K}$



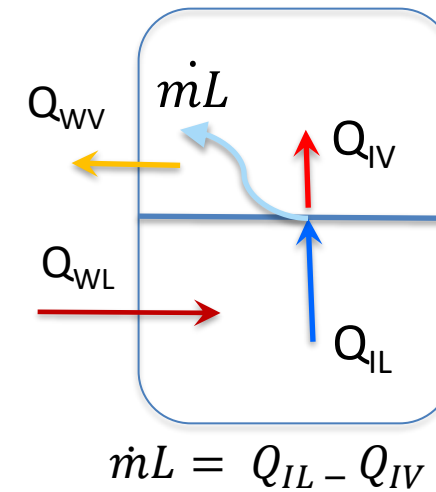
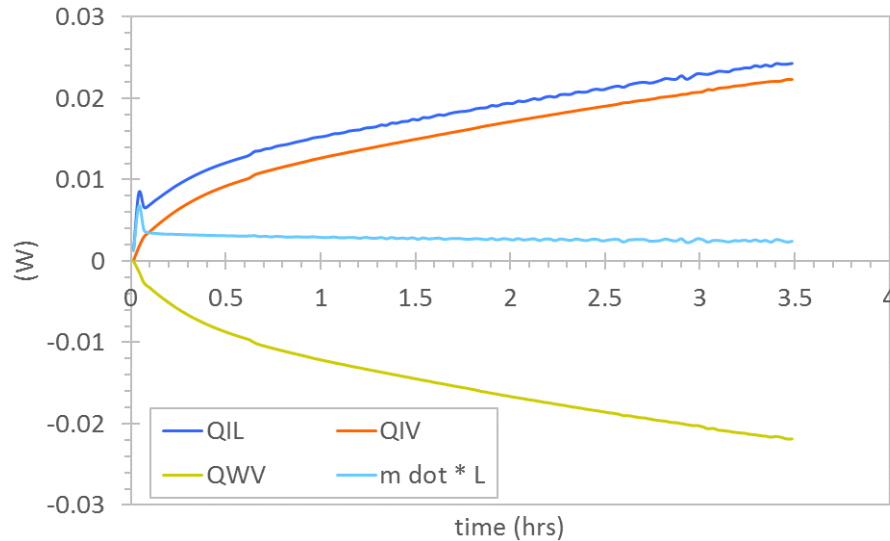
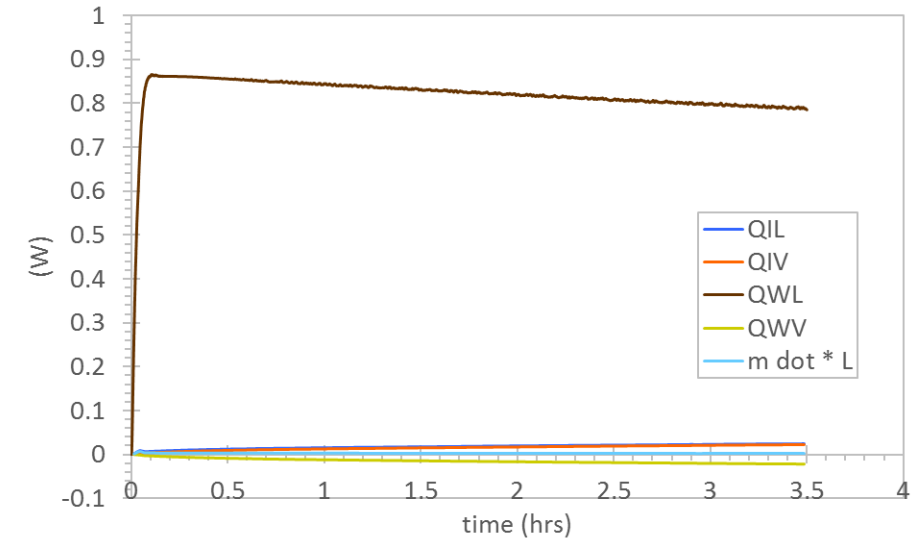
ZBOT-1G Self-Pressurization: Prediction of Heat Flow & Energy Distributions During VJ Heating



ZBOT Strip Band Heating, 1W (5.75 W/m²), 90% FL



$\{ Ra_L \rightarrow (10)^{10}, Ra_v \rightarrow (10)^7, Bo \rightarrow (10)^4 \}$



$$Q_{IL} > Q_{IV}$$

$$\dot{m} > 0$$

Evaporation

$$\dot{m}L = Q_{IL} - Q_{IV}$$

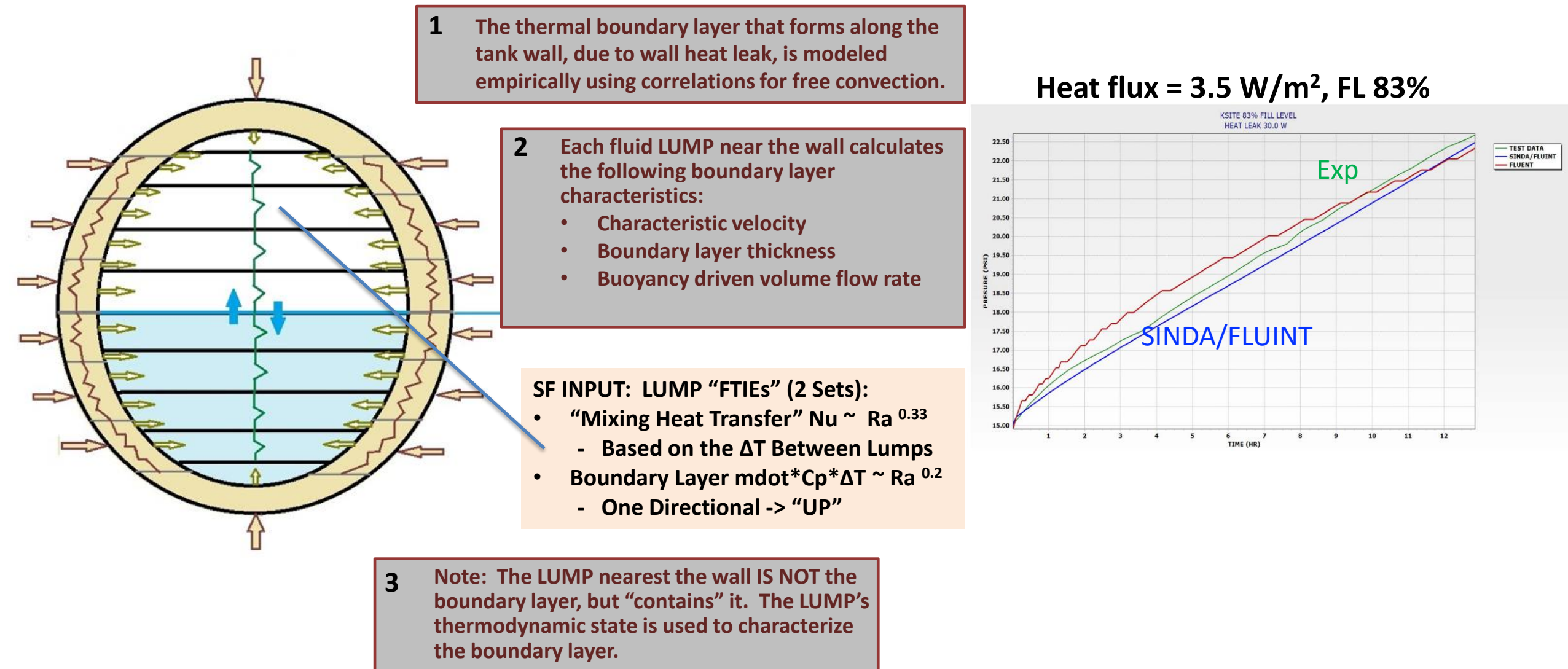


Fig 5: 1D, 2D, 3D Stratified Tank Boundary Layer and Mixing



Propellant Tank Autogenous Pressurization & Liquid Extraction in 1G

EDU Tank – 1G Autogenous Pressurization

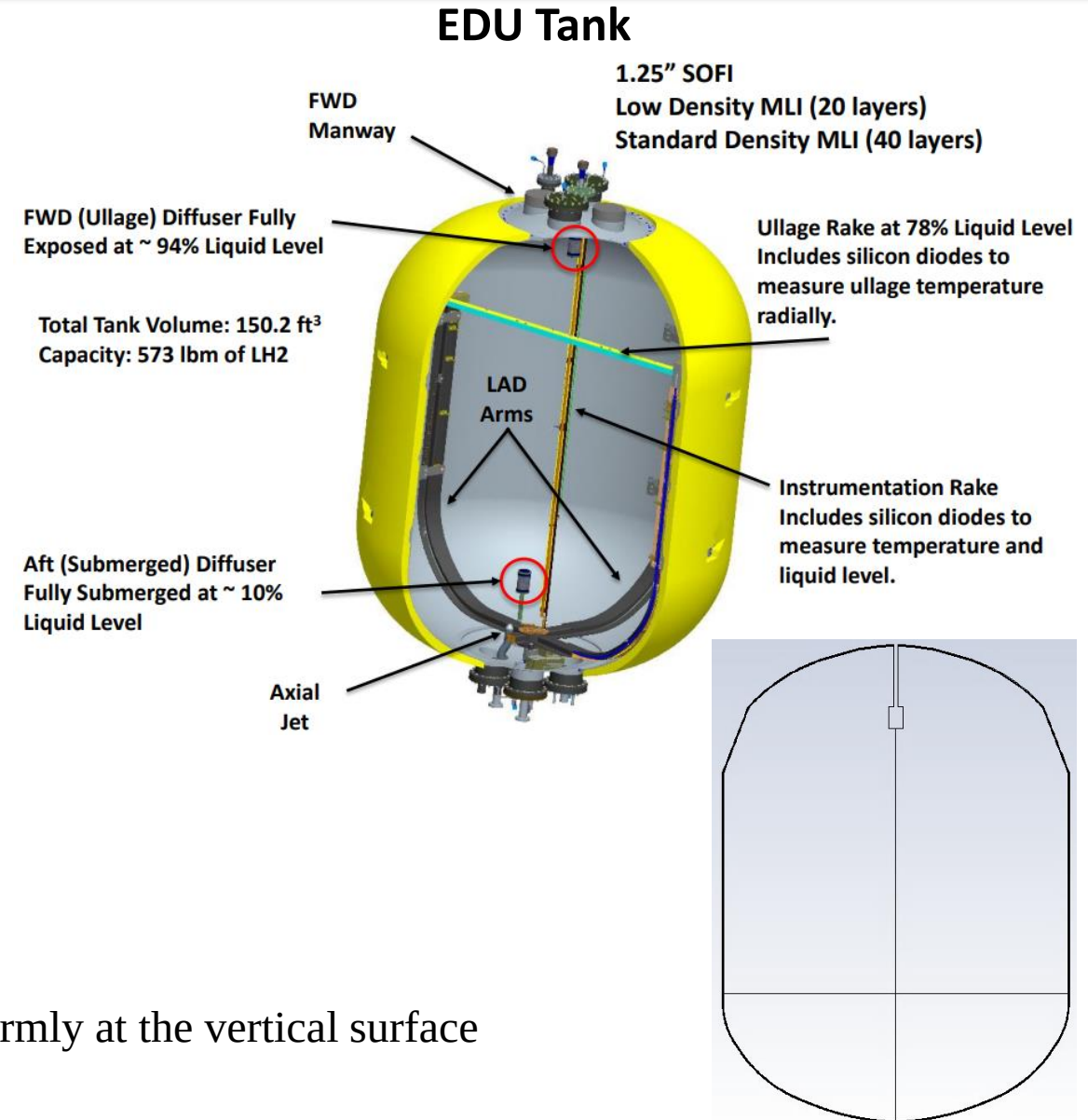


Experiment

- Testing conducted at MSFC's Test Stand 300 in 2014
- Tank $D = 1.7$ m; $V = 4.287$ m³.
- Tank wall - 6 mm aluminum with Multi-Layer Insulation (MLI)
- Gaseous N₂ flown through a diffuser at the top of the tank.
- Temperature sensors on a vertical rake, horizontal rake and on the tank wall.
- Tank fill level documented using the capacitance probe data and RFMG

CFD

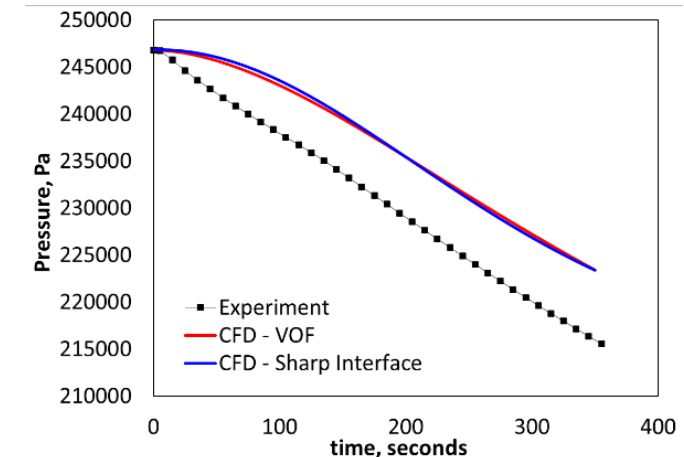
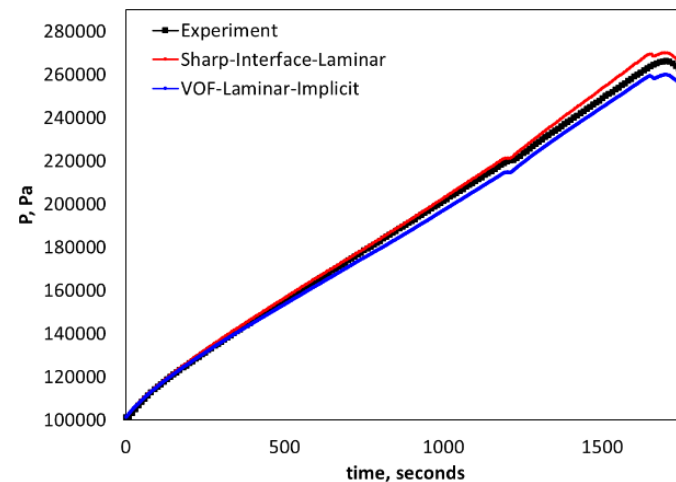
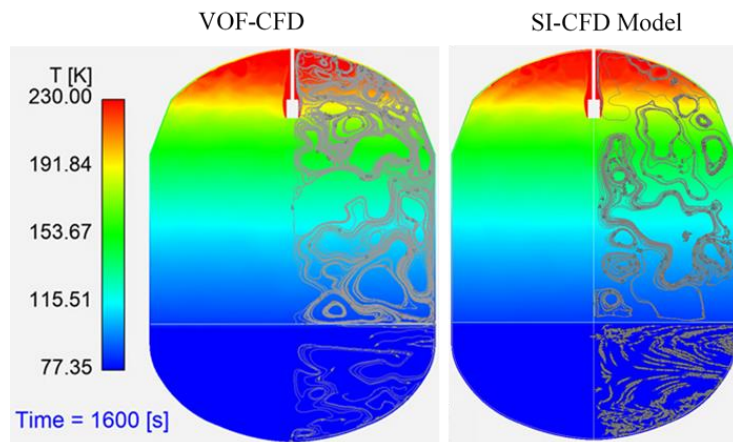
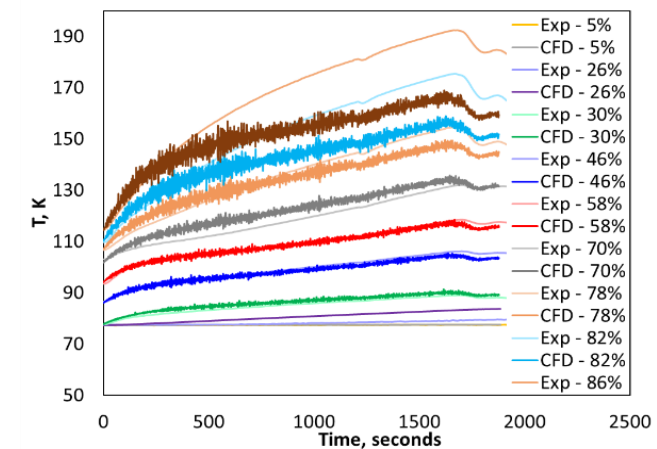
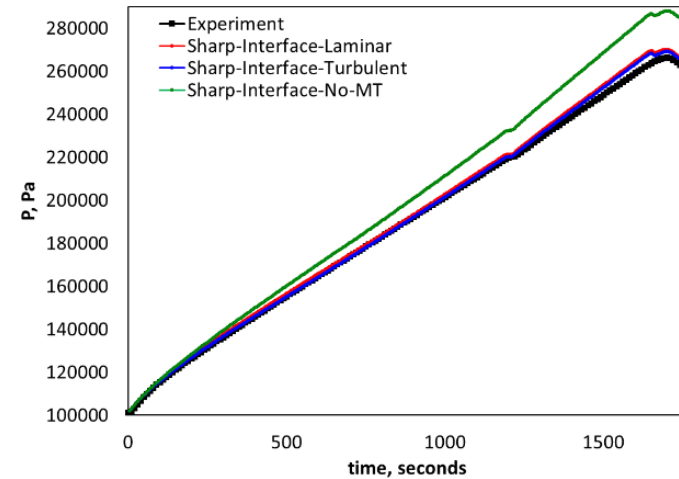
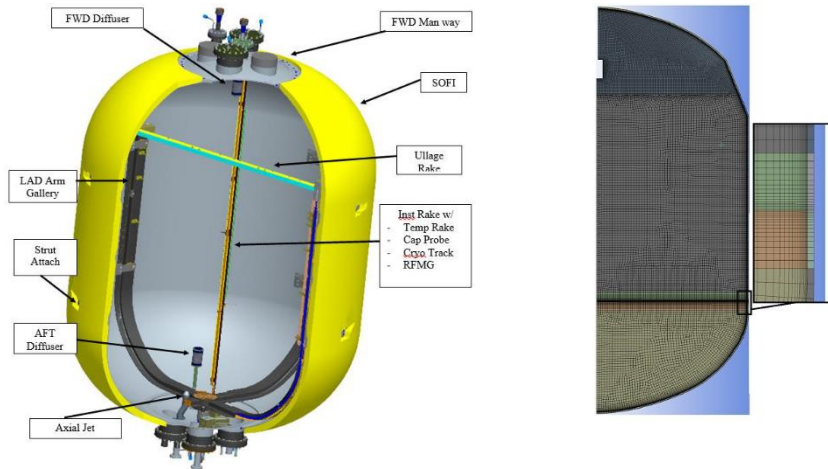
- 2D axisymmetric geometry with tank wall included
- VOF and Sharp Interface Models used
- Temperature dependent LN₂ and GN₂ properties
- Experimental Temperature profile used as Initial Conditions
- 26% fill level considered
- Measured values of mass flow rate and temperature applied uniformly at the vertical surface of the injector as B.C.



1G Validation against the EDU Autogeneous Pressurization Experiment

K-site LN2 tank autogeneous pressurization experiment
 Fill level = 26% , $T_o = 77.35$ K, and $P_o = 101270$ Pa
 $D = 1.7$ m, Volume ~ 4.287 m³

Inlet GN2 flow rate is ~ 0.008 kg/s and Gas T plateaus to 285 K.
 But time-dependent experimental values were used as input to the model

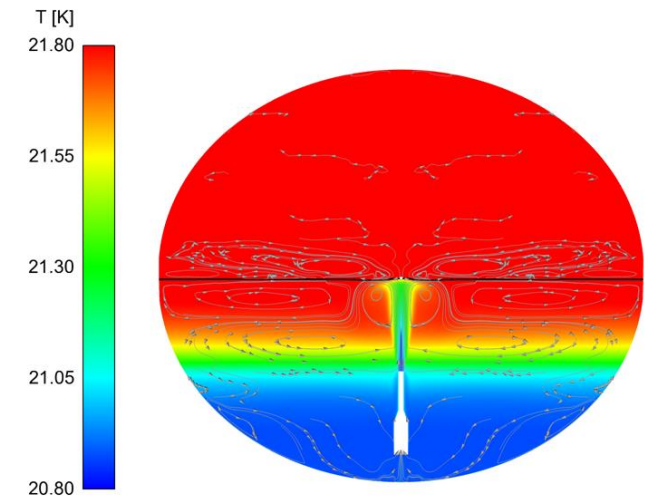
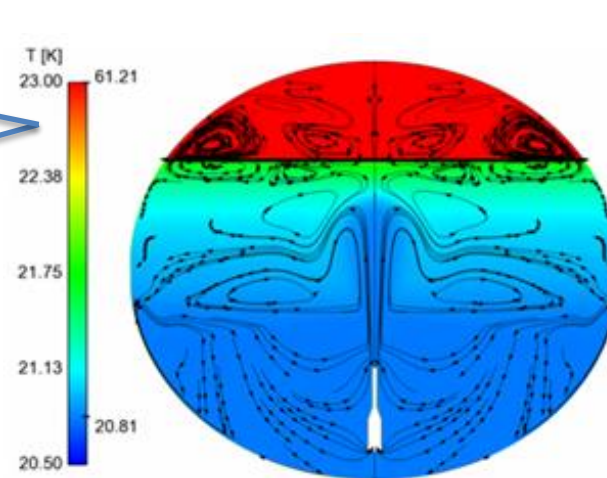
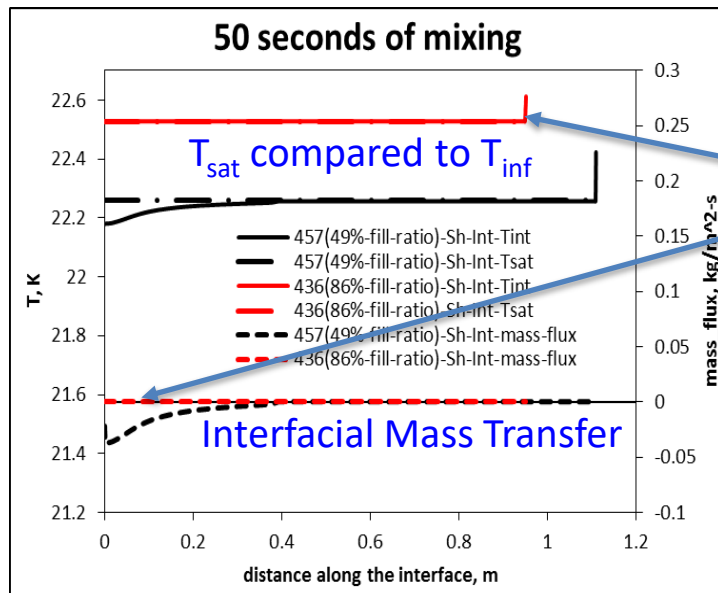
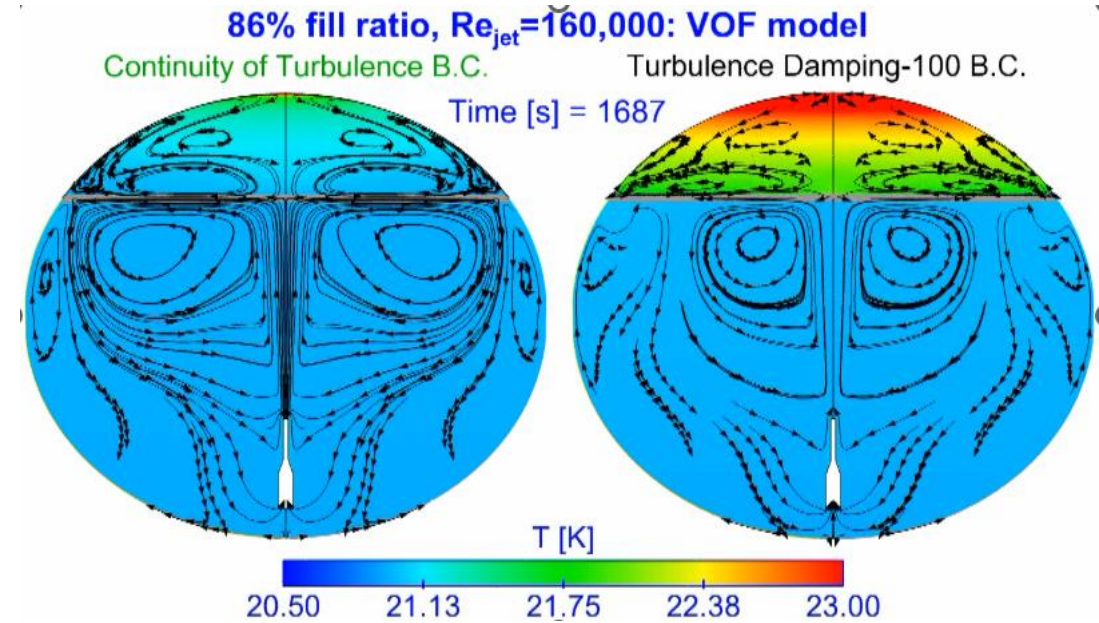
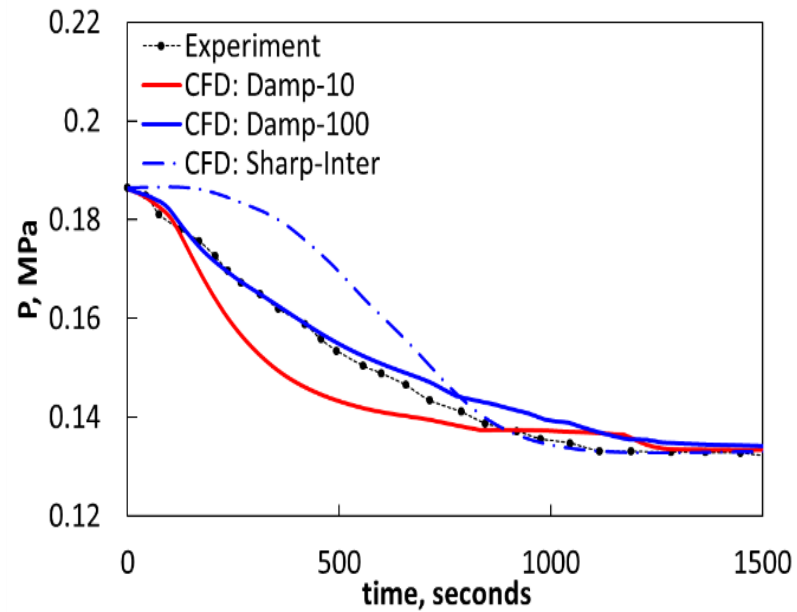
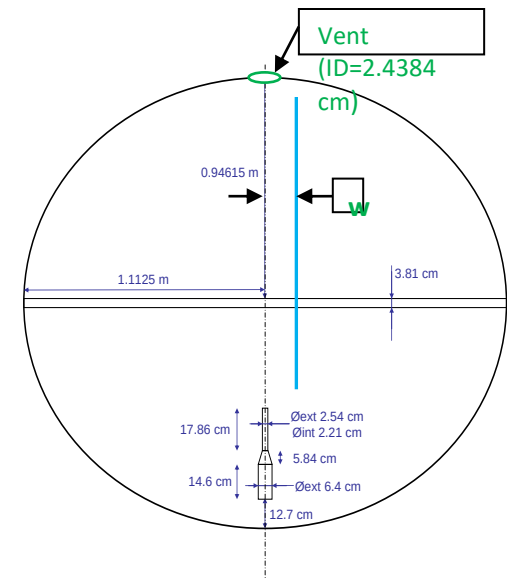




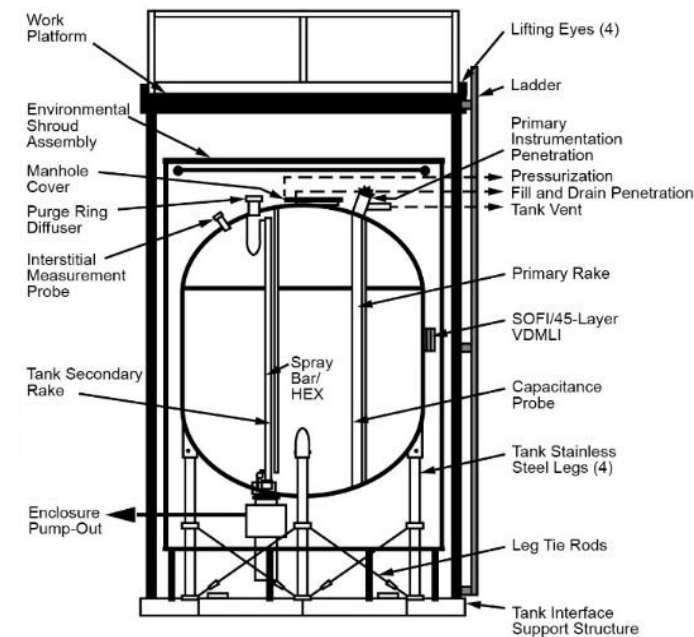
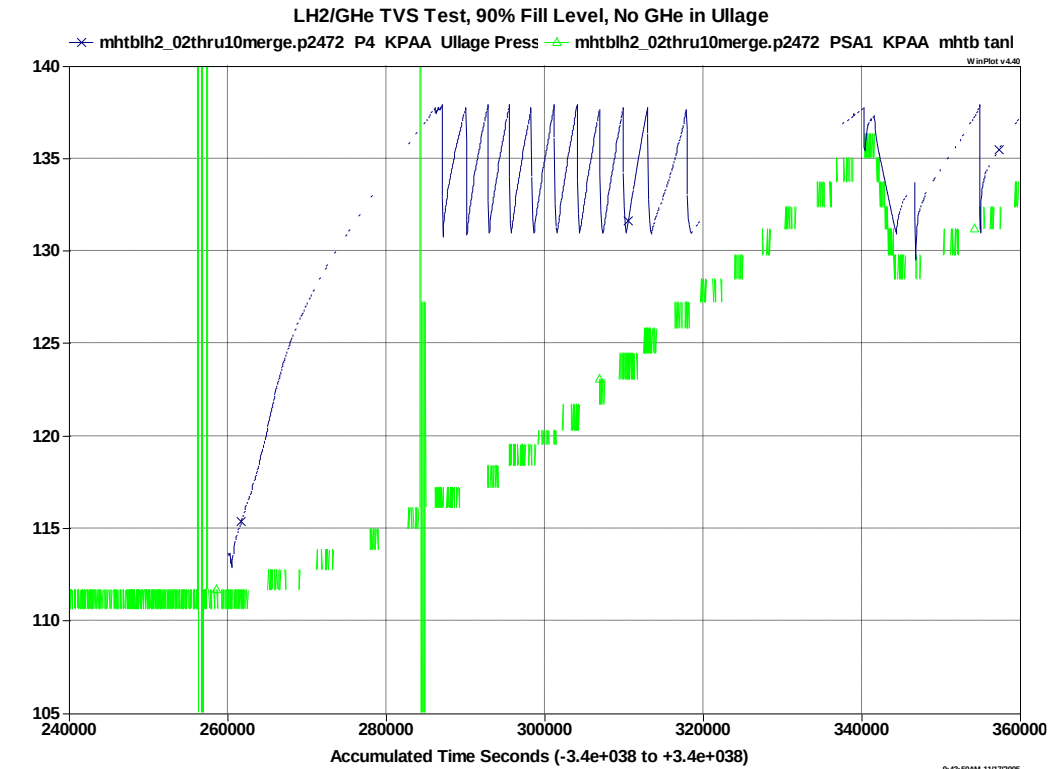
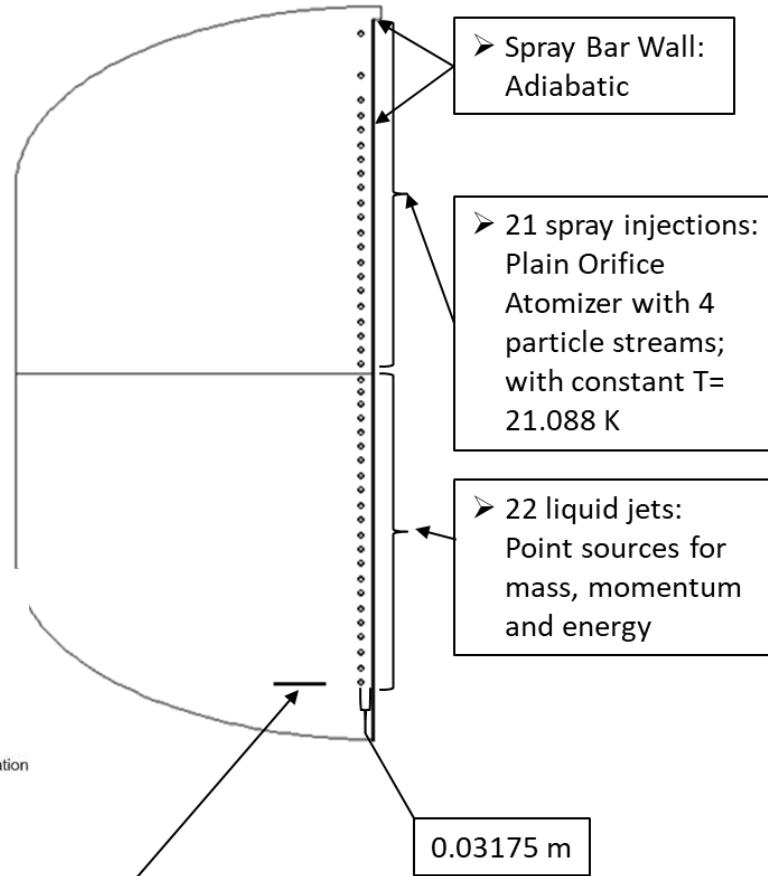
Propellant Tank Pressure Control:
Ground-Based Experiments and Model Simulation

Pressure Control Experiments at the GRC K-site Facility (1990-91)

FL: 49% & 86% Vjet 2.5 m/s $Re_{jet} = 1.6(10)^5$



Spray-Bar Droplet Injection Pressure Control Experiments at the MHTB Facility (2000)



➤ Pump: Area averaged sink for mass, momentum and energy

Liquid flow rate: $0 \Rightarrow 7.5447\text{e-}4\text{ kg/s}$.

Computational Model Description: Droplet Mass Transfer Model



Particle Energy Equation:

$$m_p c_p \frac{dT_p}{dt} = h \cdot A_p (T_\infty - T_p) - L \dot{m}_p$$

Schrage model:

$$|\dot{m}| = \left(\frac{2\sigma}{2 - \sigma} \right) \left(\frac{M}{2\pi R} \right)^{1/2} \left(\frac{P_i}{T_i^{1/2}} - \frac{P_v}{T_v^{1/2}} \right)$$



Droplet (Particle) Temperature is calculated from the Particle Energy Equation

Droplets summary after 0.01s Time Step

Number of injections	21
Injector inner diameter	1.70e-03 m
Total number of parcels	84
Total number of droplets	2880
Total mass of droplets	1.20e-04 kg
Maximum droplet diameter	1.46e-03 m
Minimum droplet diameter	8.06e-04 m
Overall mean diameter	1.00e-03 m

Tsat model:

$$\text{if } T_p < T_{sat}(P_v) \Rightarrow \dot{m}_p = 0;$$

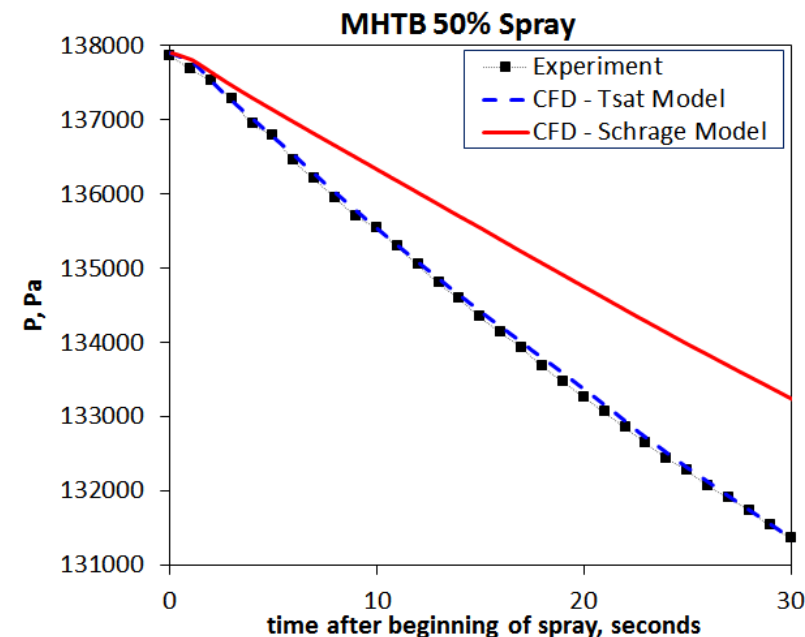
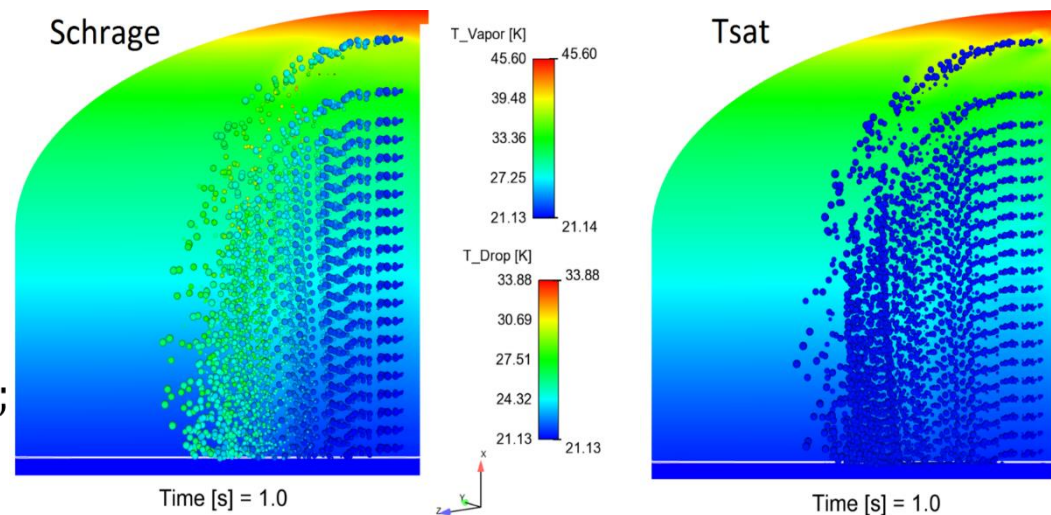


T_p is calculated from the Particle Energy Equation

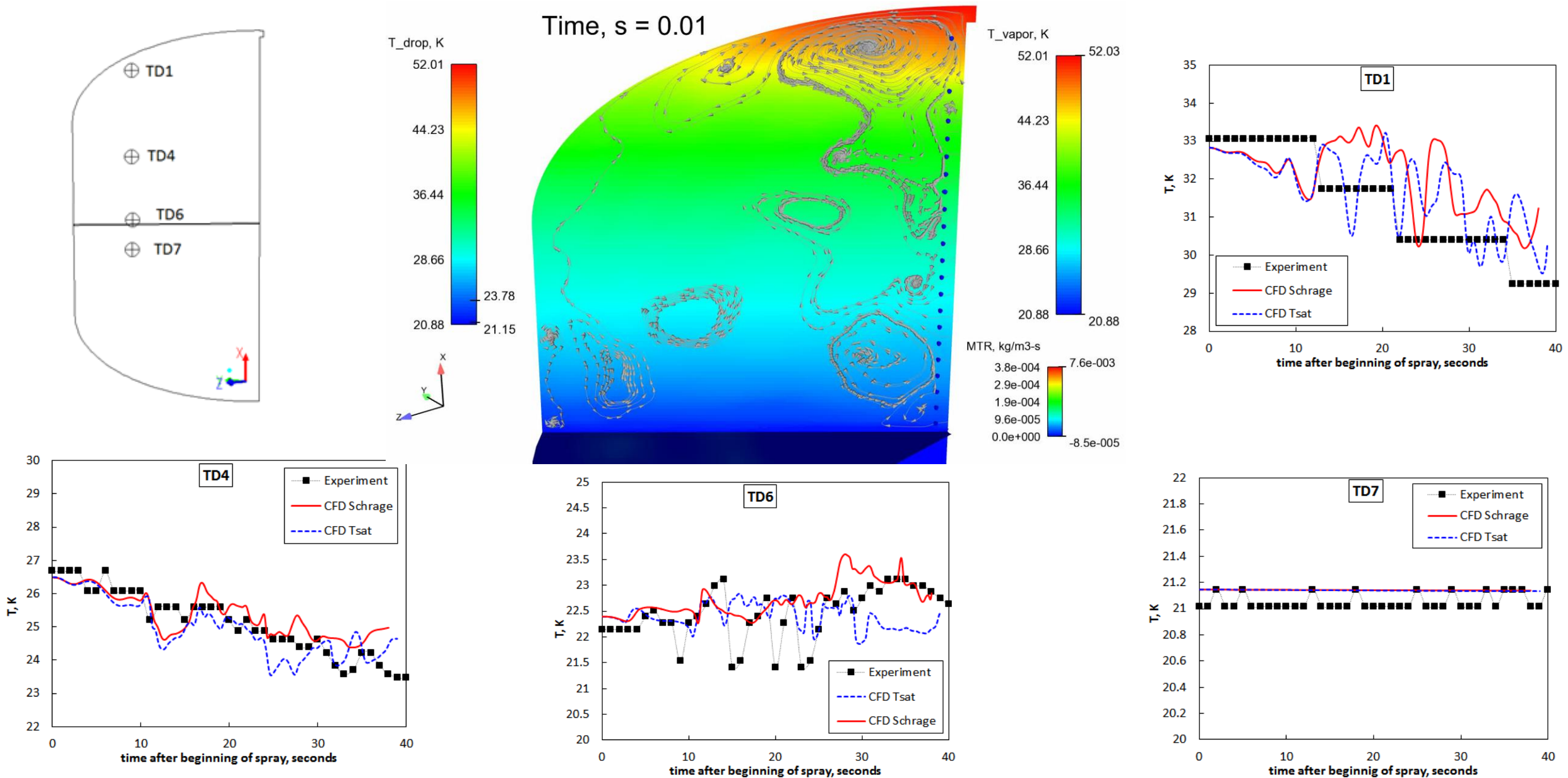
$$\text{if } T_p \geq T_{sat}(P_v) \Rightarrow T_p = T_{sat}(P_v)$$



$\dot{m}_p$ is calculated from the Particle Energy Equation



Spray-Bar Droplet Injection Pressure Control Experiments at the MHTB Facility (2000)





Tank Chillumdown:

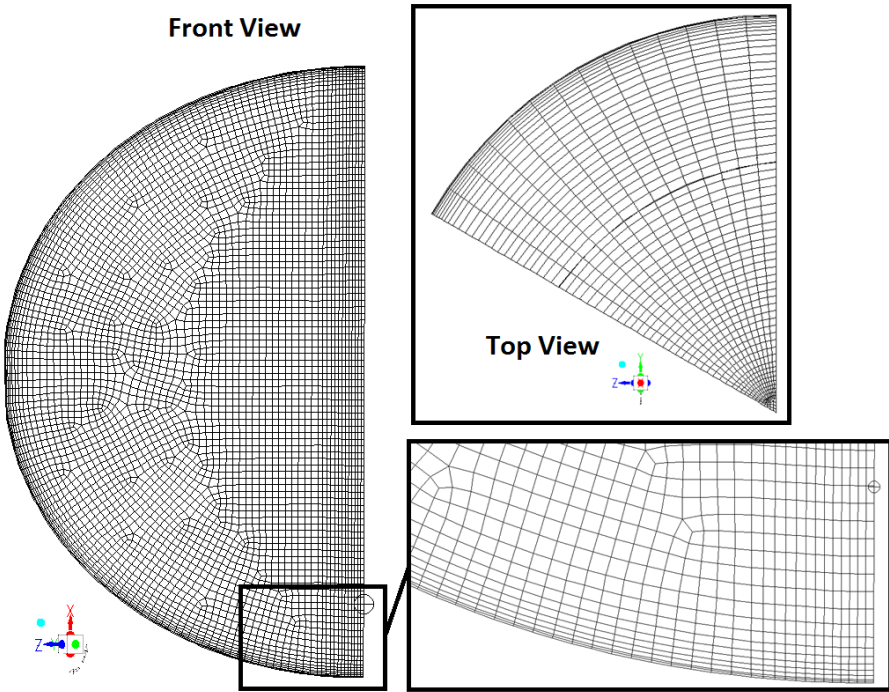
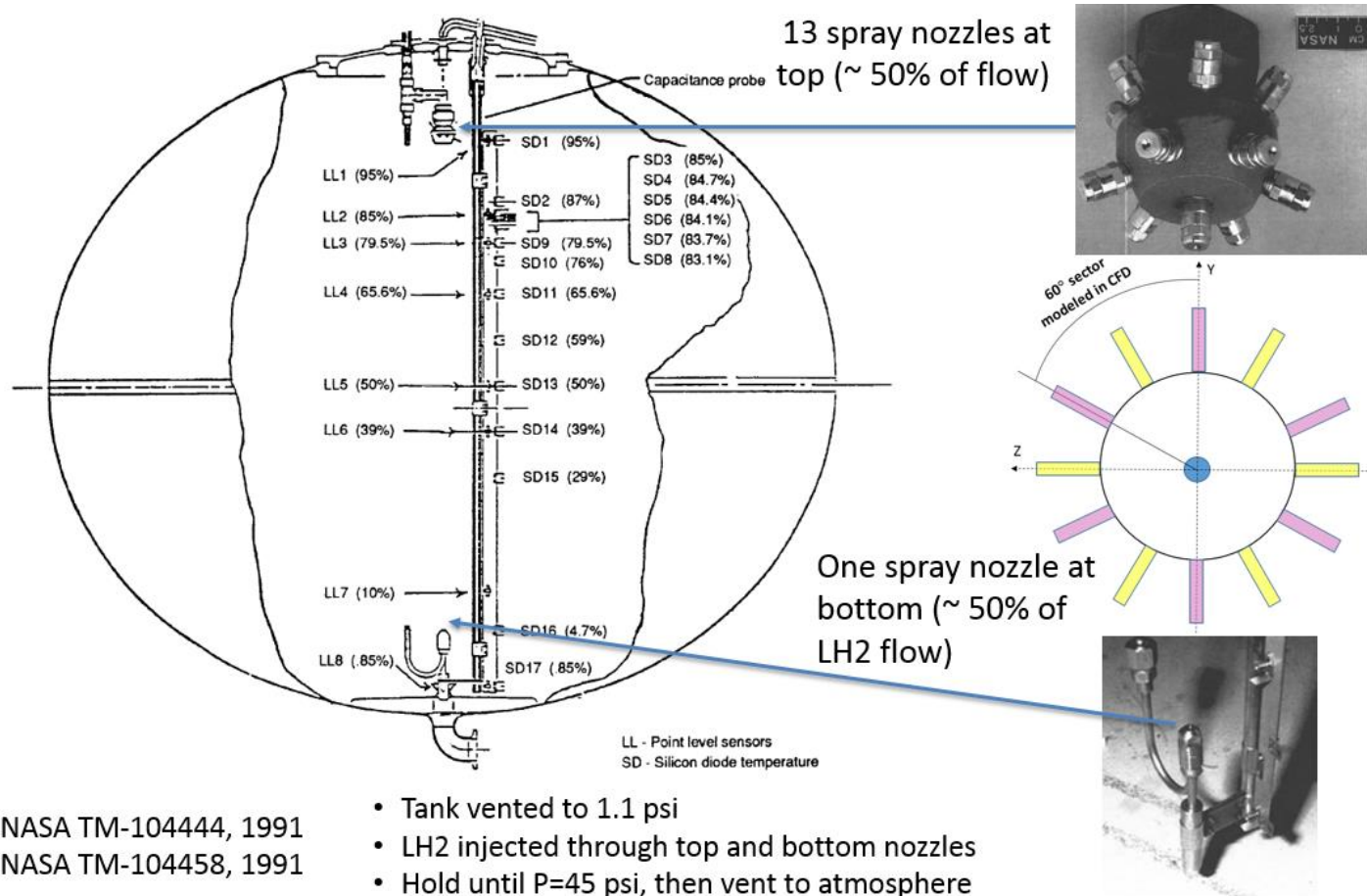
1G Experiment and Model Simulation

K-Site Charge-Hold-Vent Tank Chillydown Experiment



- CFD study based on 1991 K-Site chillydown experiment
- Tank is **ellipsoidal** volume of revolution: $D_{\text{major}} = 2.2 \text{ m}$, major-to-minor axis ratio = 1.2
- Working Fluid: Liquid and Vapor **Hydrogen**

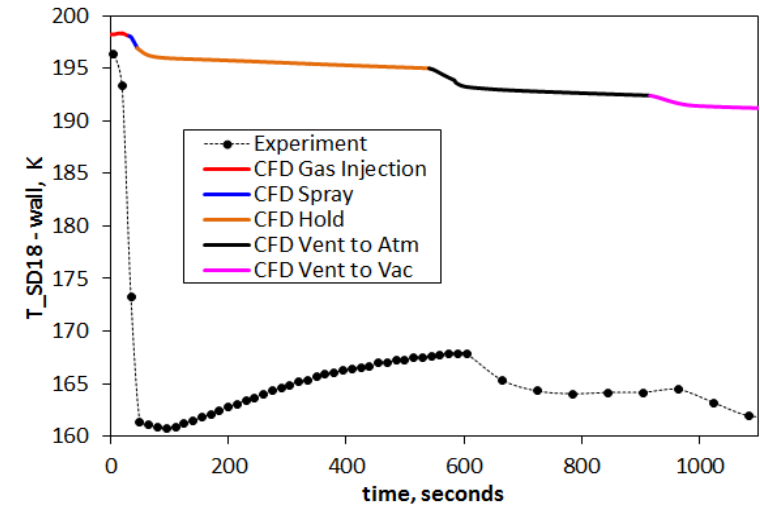
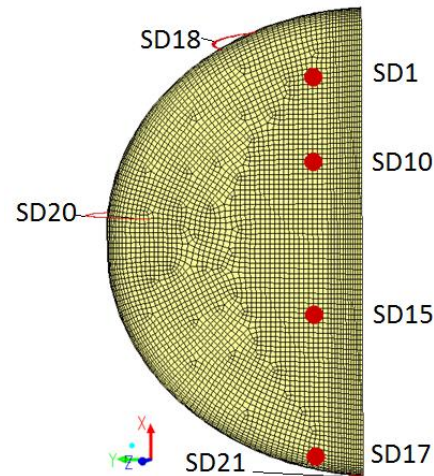
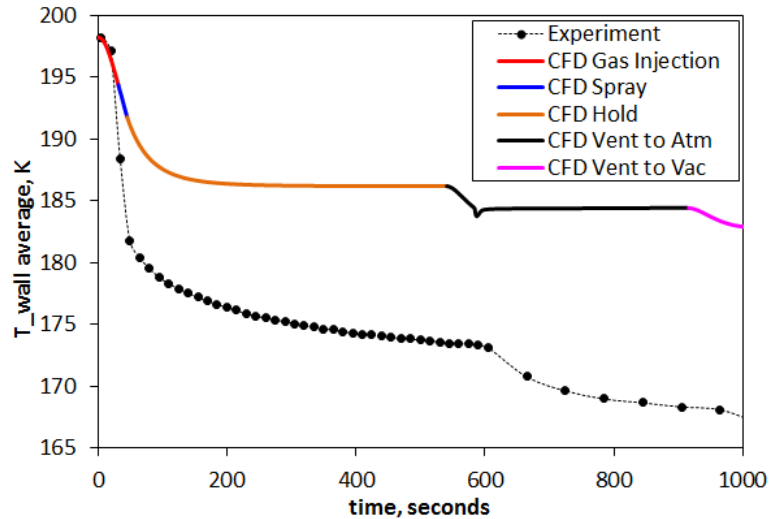
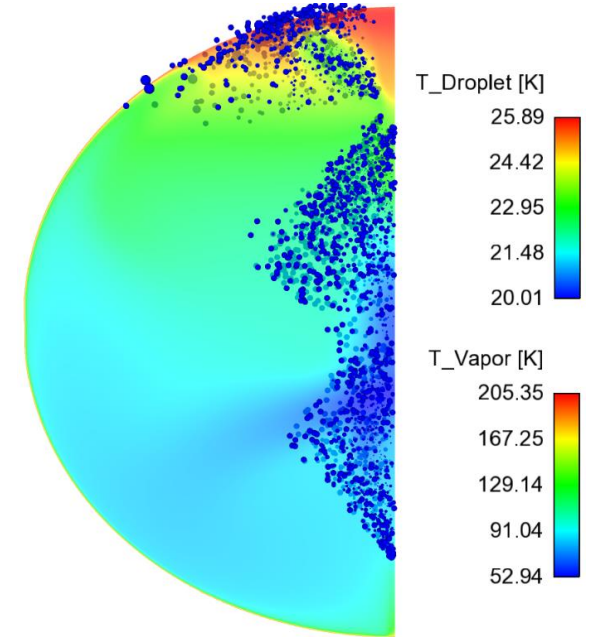
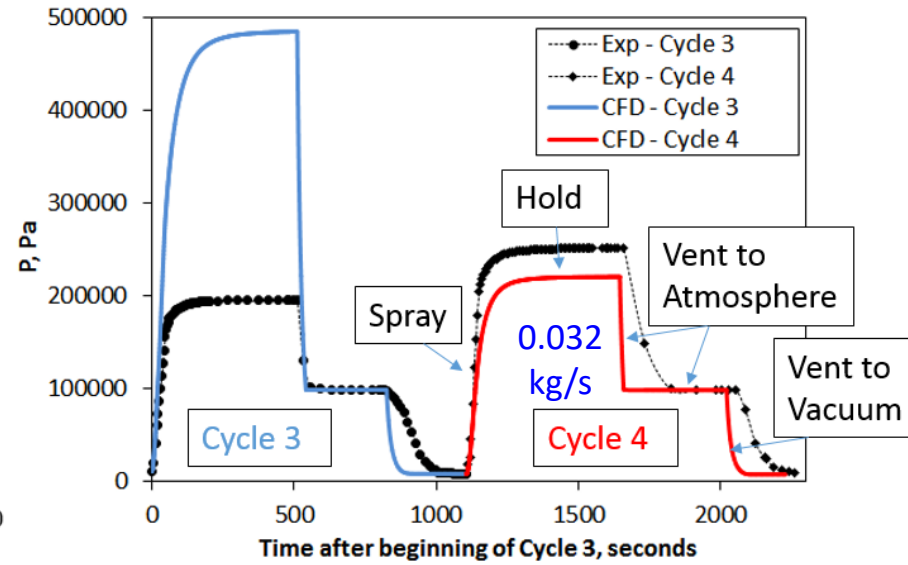
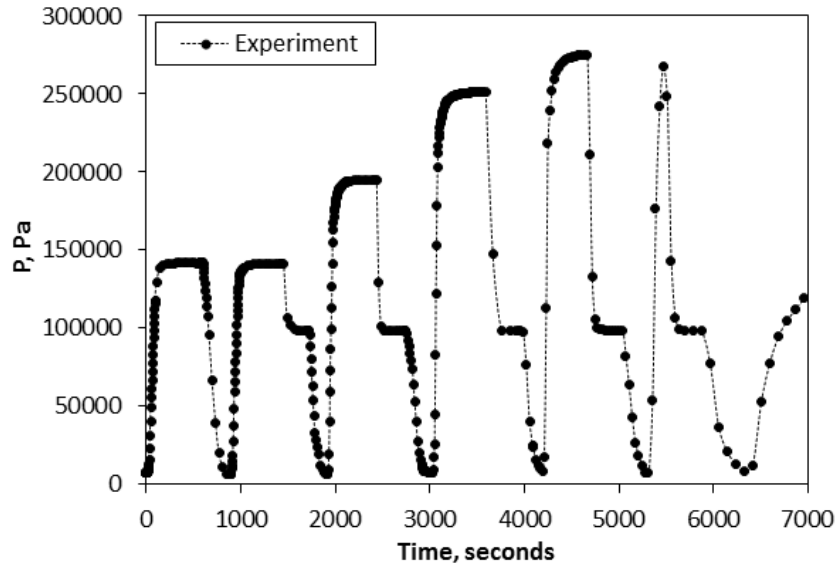
Computational Model Description: Mesh and Domain



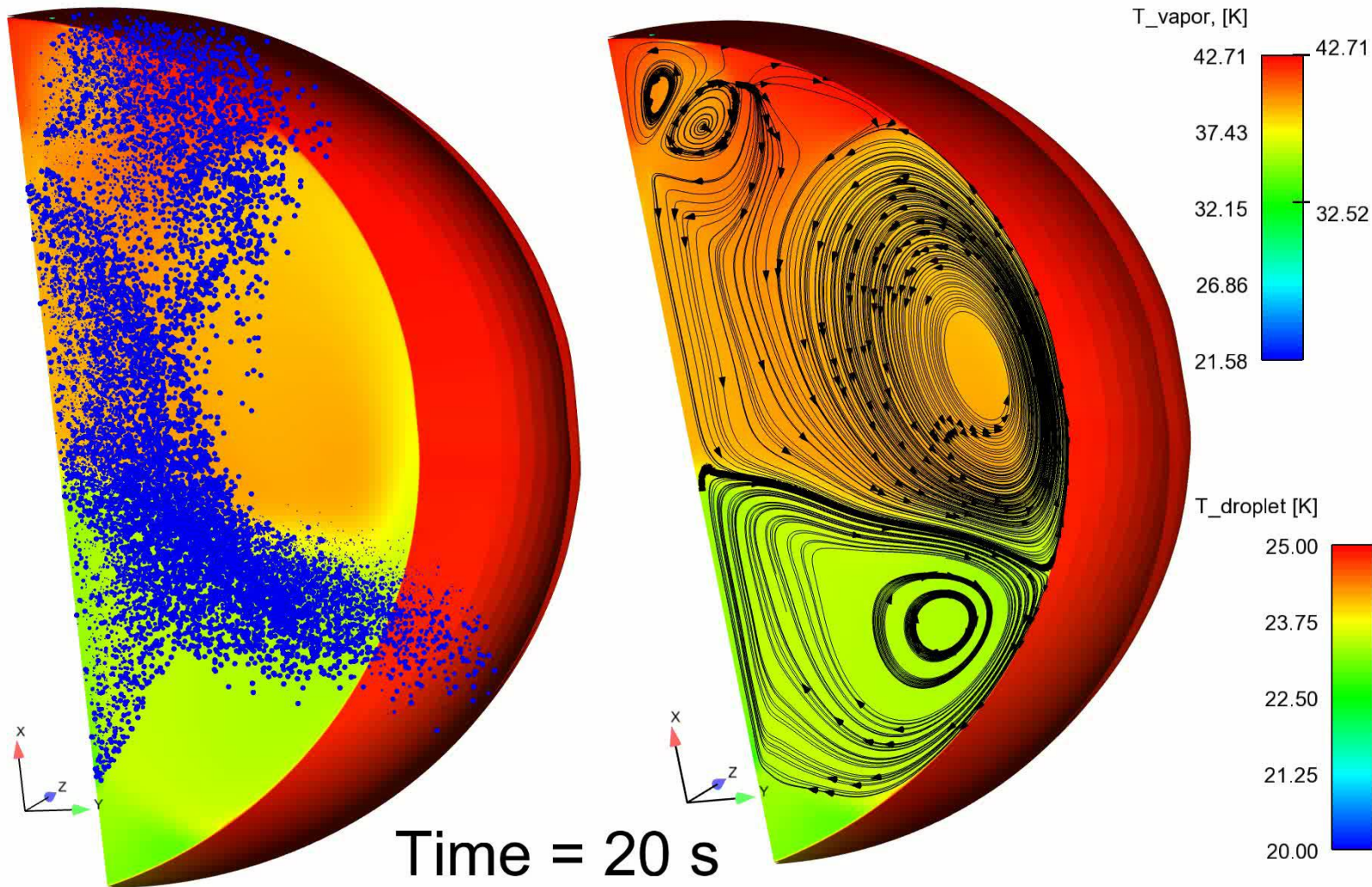
- 60° sector computational mesh with 71,214 cells

- Tank vented to 1.1 psi
- LH2 injected through top and bottom nozzles
- Hold until P=45 psi, then vent to atmosphere

K-Site Charge-Hold-Vent Tank Chardown Experiment CFD Simulation



K-Site Charge-Hold-Vent Tank Chillardown Experiment CFD Simulation



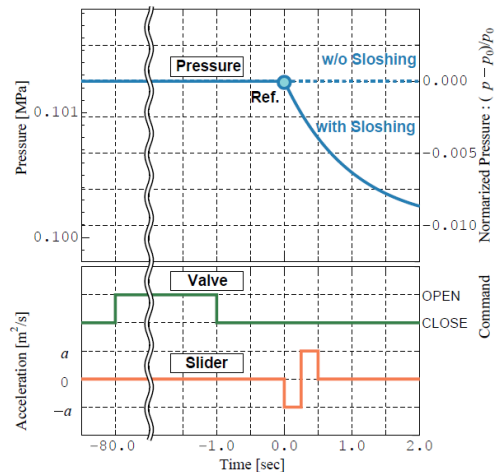
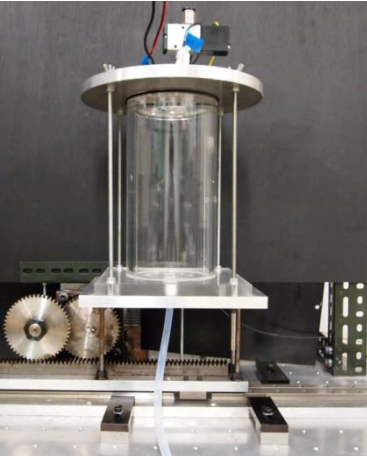
Time = 20 s

- ❖ A new sub-model was developed for allowing liquid accumulation in the tank. It was demonstrated that this model produces physically intuitive and consistent results.
- ❖ In-house developed user subroutines utilized in this model for:
 - Droplet-vapor heat and mass transfer
 - Droplets converting into liquid and forming interface at the tank walls
 - Droplets joining an existing interface
 - Mass transfer at the liquid-vapor interface
- ❖ A model for liquid film formation and rapid evaporation on the tank walls is necessary for accurate modeling of the chilldown process



Slosh Dynamics & Pressure Collapse in 1G

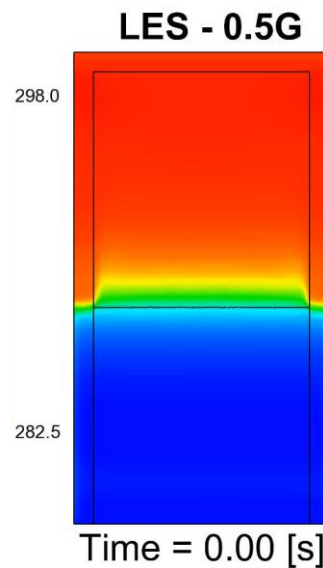
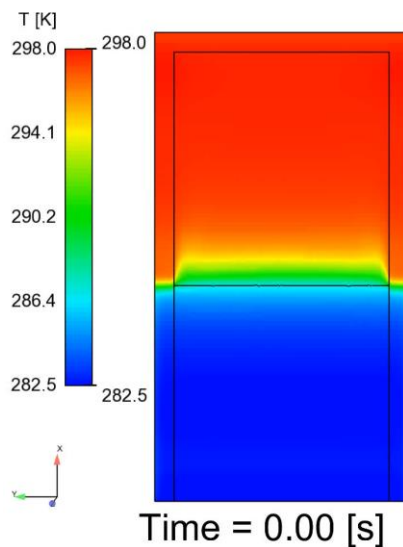
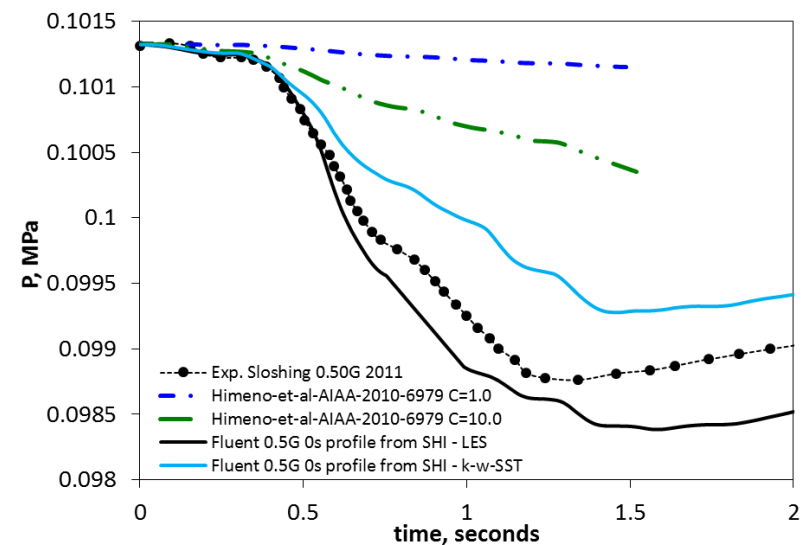
1G Validation against JAXA/UoT: Silicone Oil Slosh without Phase Change



Effect of turbulence modeling (RANS models vs. LES)

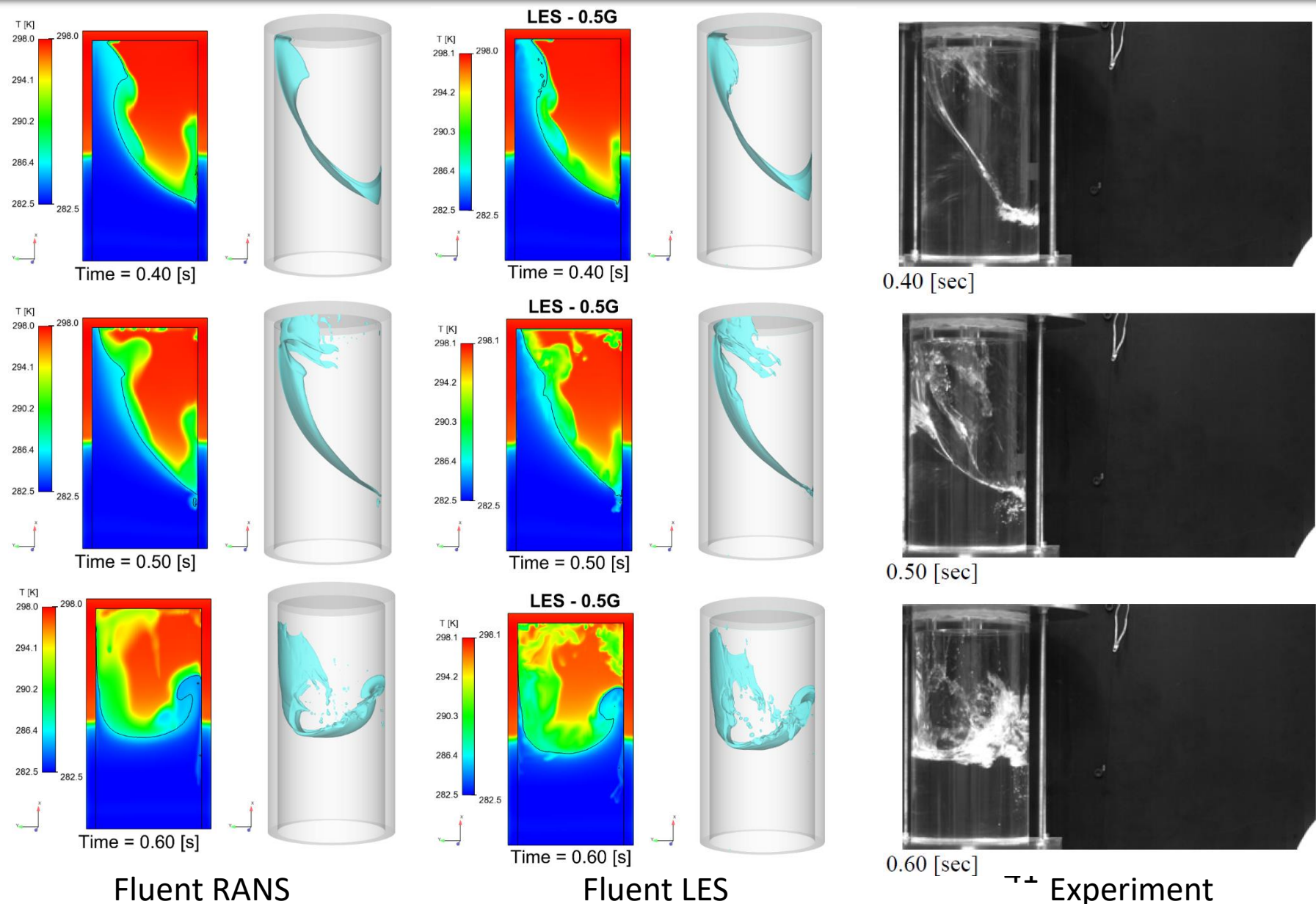
RANS

LES



Lateral acceleration = 0.5G

1G Validation against JAXA/UoT: **Silicone Oil Slosh without Phase Change**

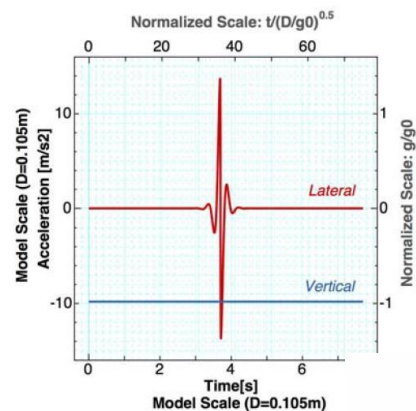
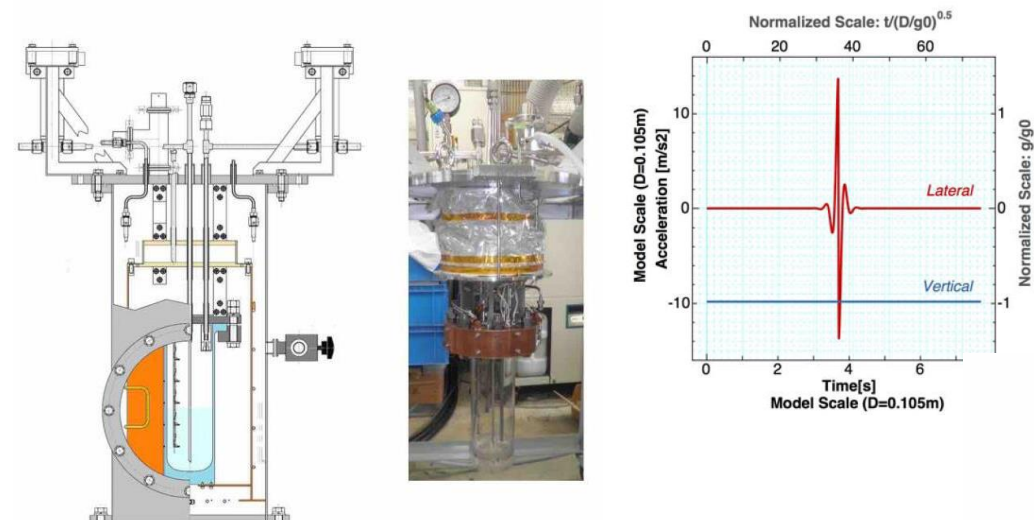


0.4 s

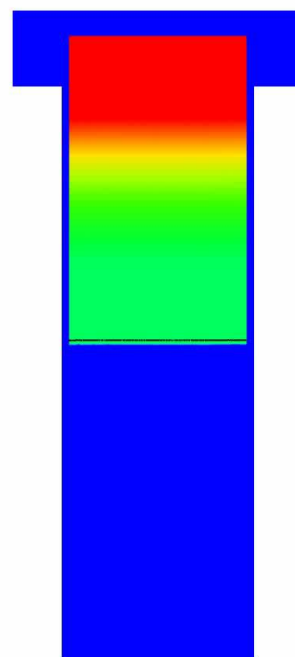
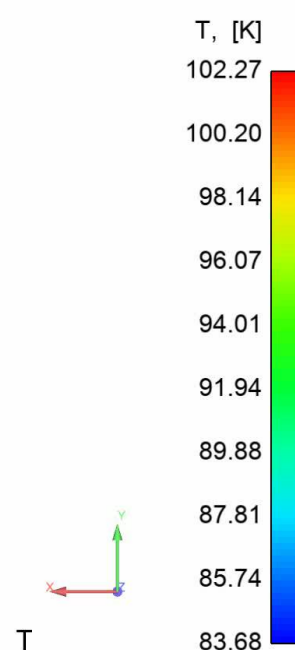
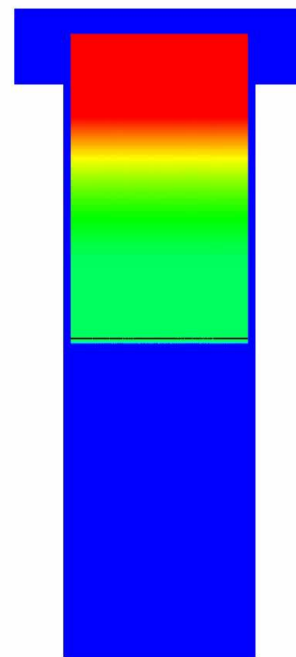
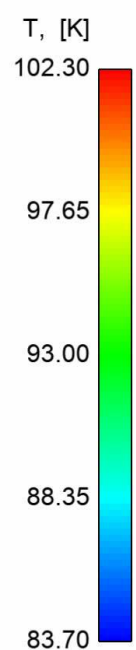
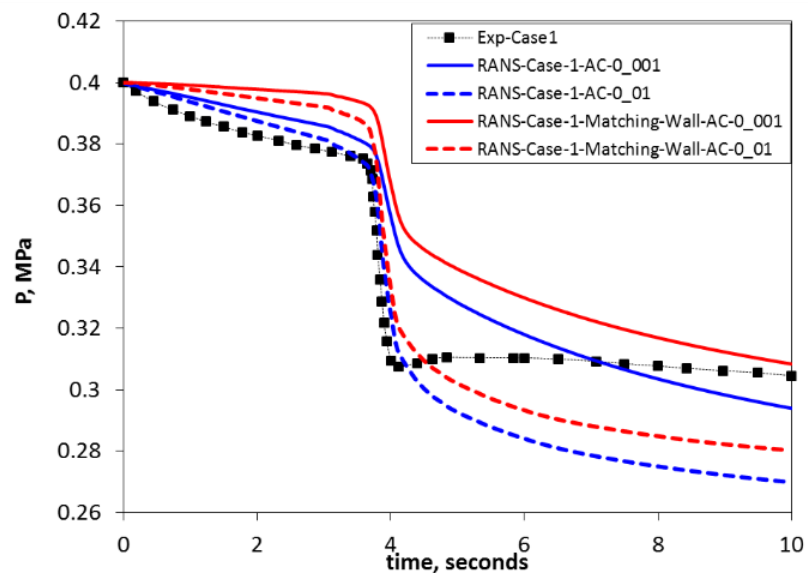
0.5 s

0.6 s

1G Validation against JAXA/UoT: LN2/GN2 – Slosh with Phase Change



Effect of turbulence model (RANS vs. LES)



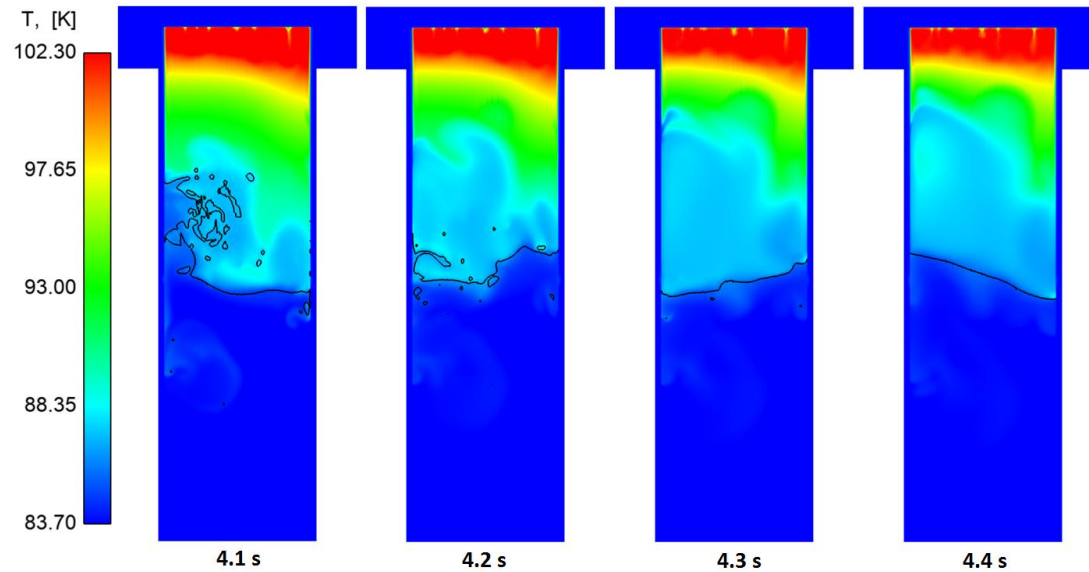
Time = 0.00 s

(Himeno et al, *AIAA-2010-6979* & *AIAA 2018-4755*)

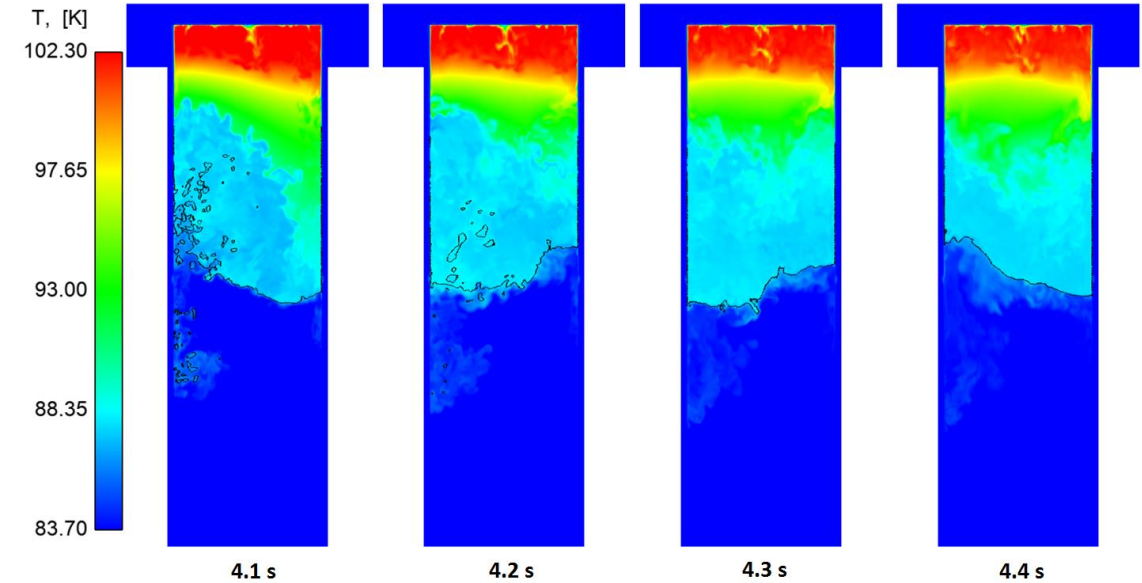
1G Validation against JAXA/UoT: LN2/GN2 – Slosh with Phase Change



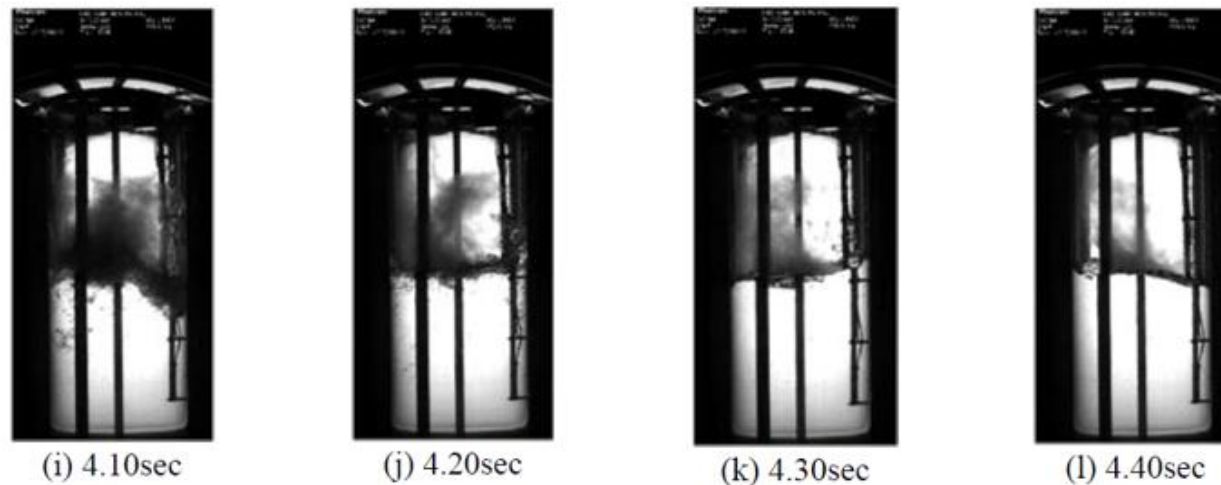
RANS



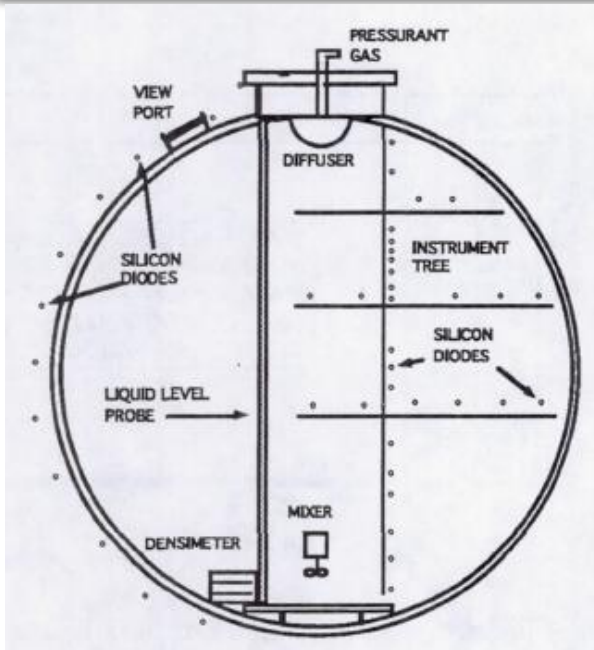
LES



Experiment



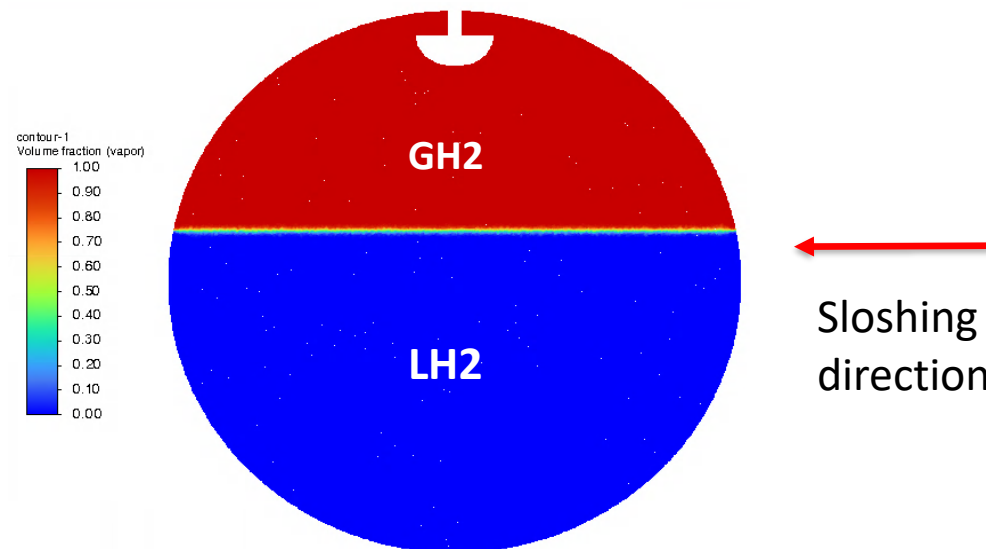
The Ground-Based K-Site Hydrogen Slosh Experiment



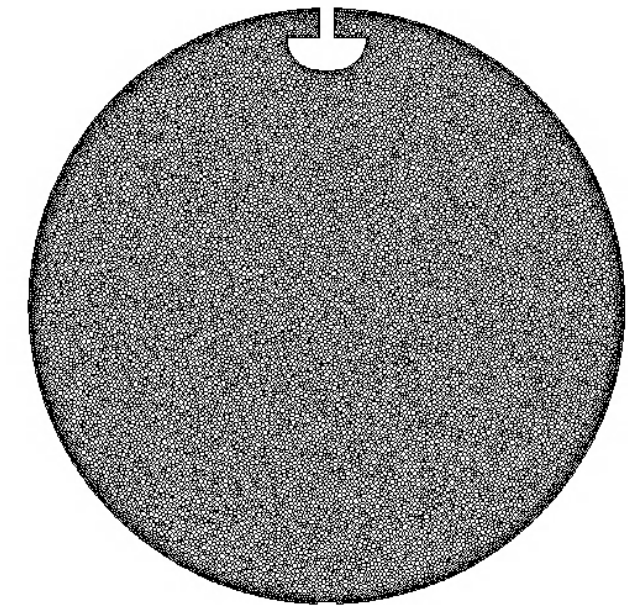
Pressurization

Initial Conditions before Pressurization (Ramp):

- 36% initial ullage volume (64% liquid fill level)
- $P_{init} = 14.6 \text{ psia} = 100660.0 \text{ Pa}$
- T_{init} (at the interface and in the liquid) = $T_{sat}(P_{init}) = 20.249 \text{ K}$
- Vapor temperatures from experimental values (axial profile)
- Wall temp match fluid temperatures at the same axial position



- Sloshing cases **870** (frequency of 0.75 Hz and amplitude of $\pm 1.5 \text{ in}$), **869** (frequency of 0.95 Hz and amplitude of $\pm 0.5 \text{ in}$) modeled



3.8 million cells

Moran, M. E., McNelis, N. B., Kudlac, M. T., Haberbusch, M. S., Satorino, G.A., "Experimental Results of Hydrogen Slosh in a 62 Cubic Foot (1750 Liter) Tank," NASA TM-106625, 1994

The Ground-Based K-Site Hydrogen Slosh Experiment – Pressurization

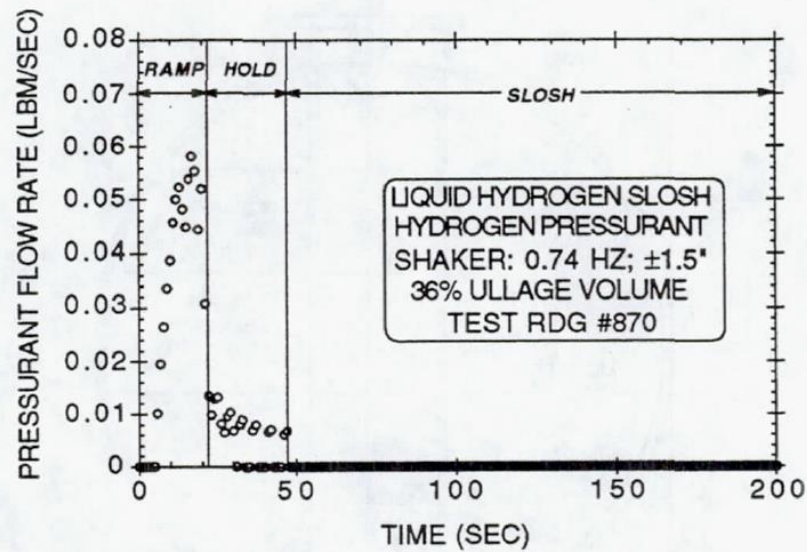
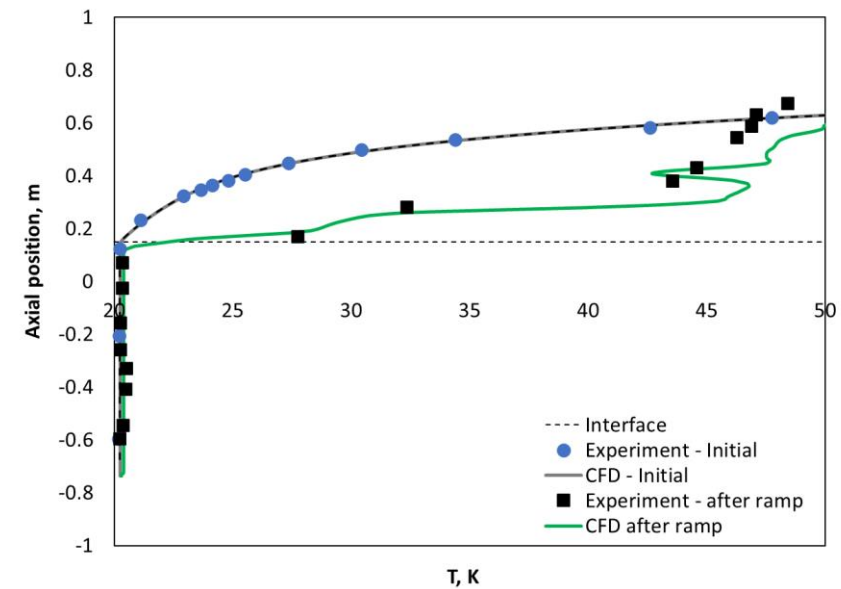
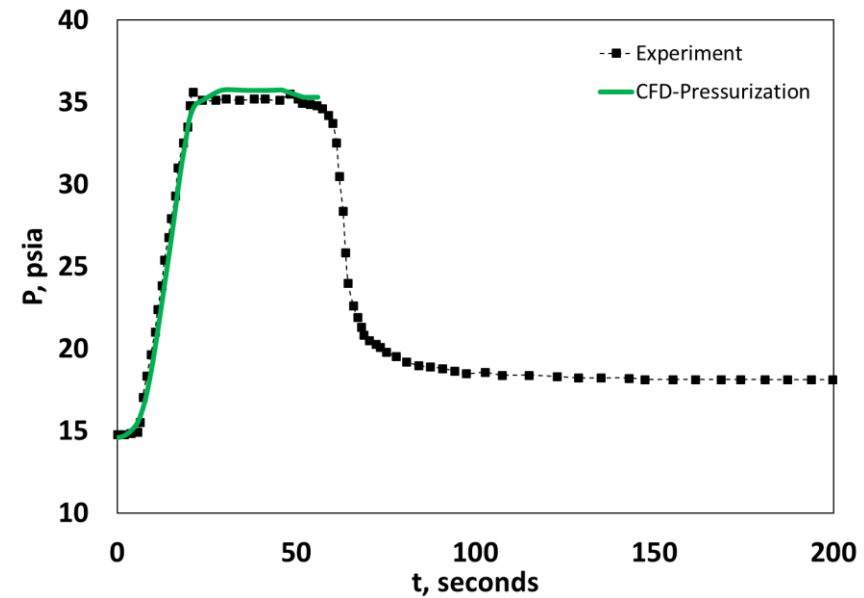
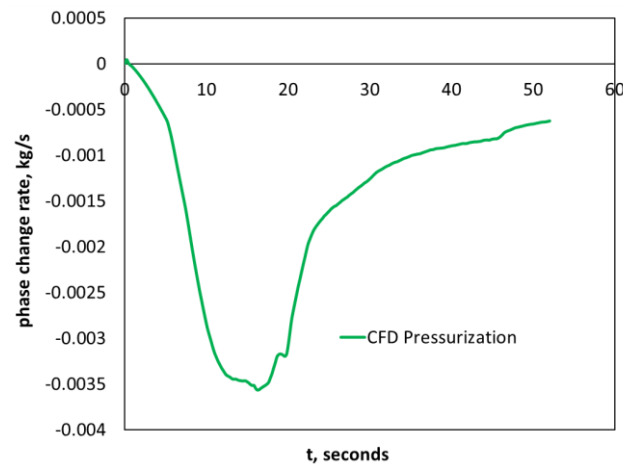
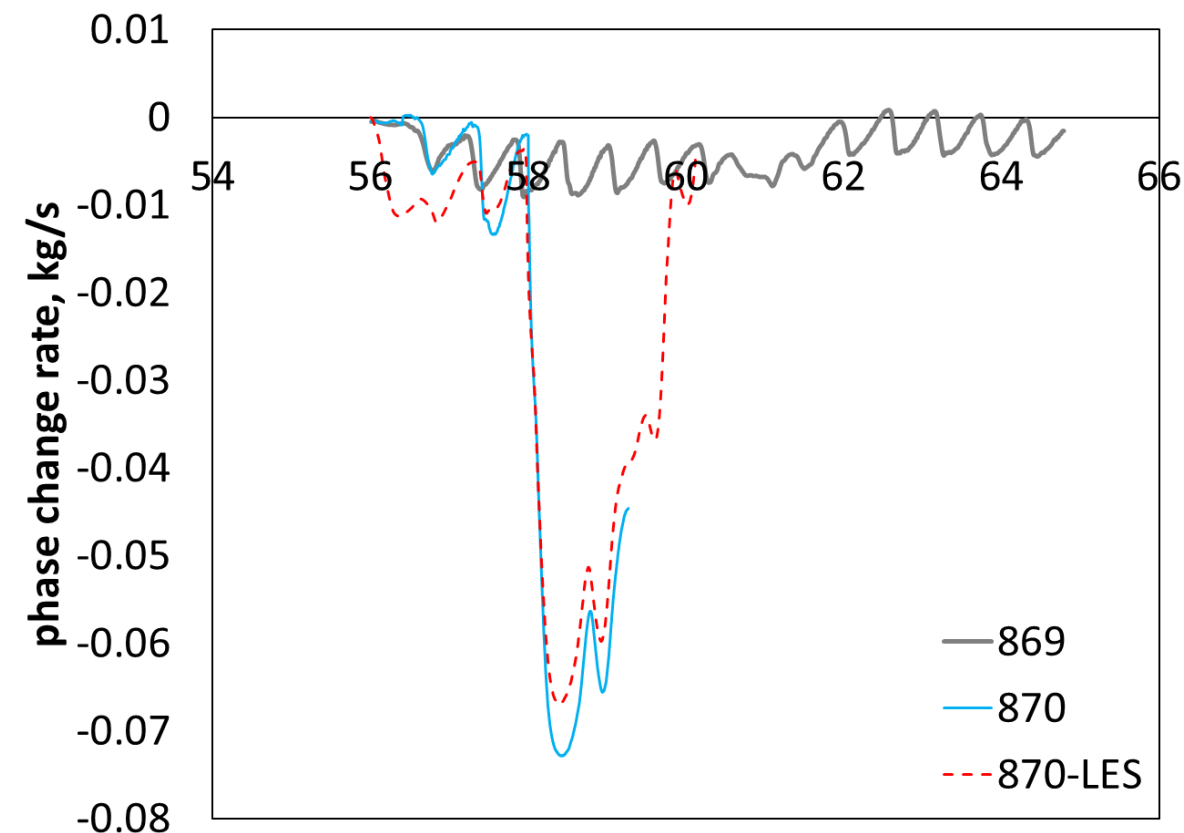
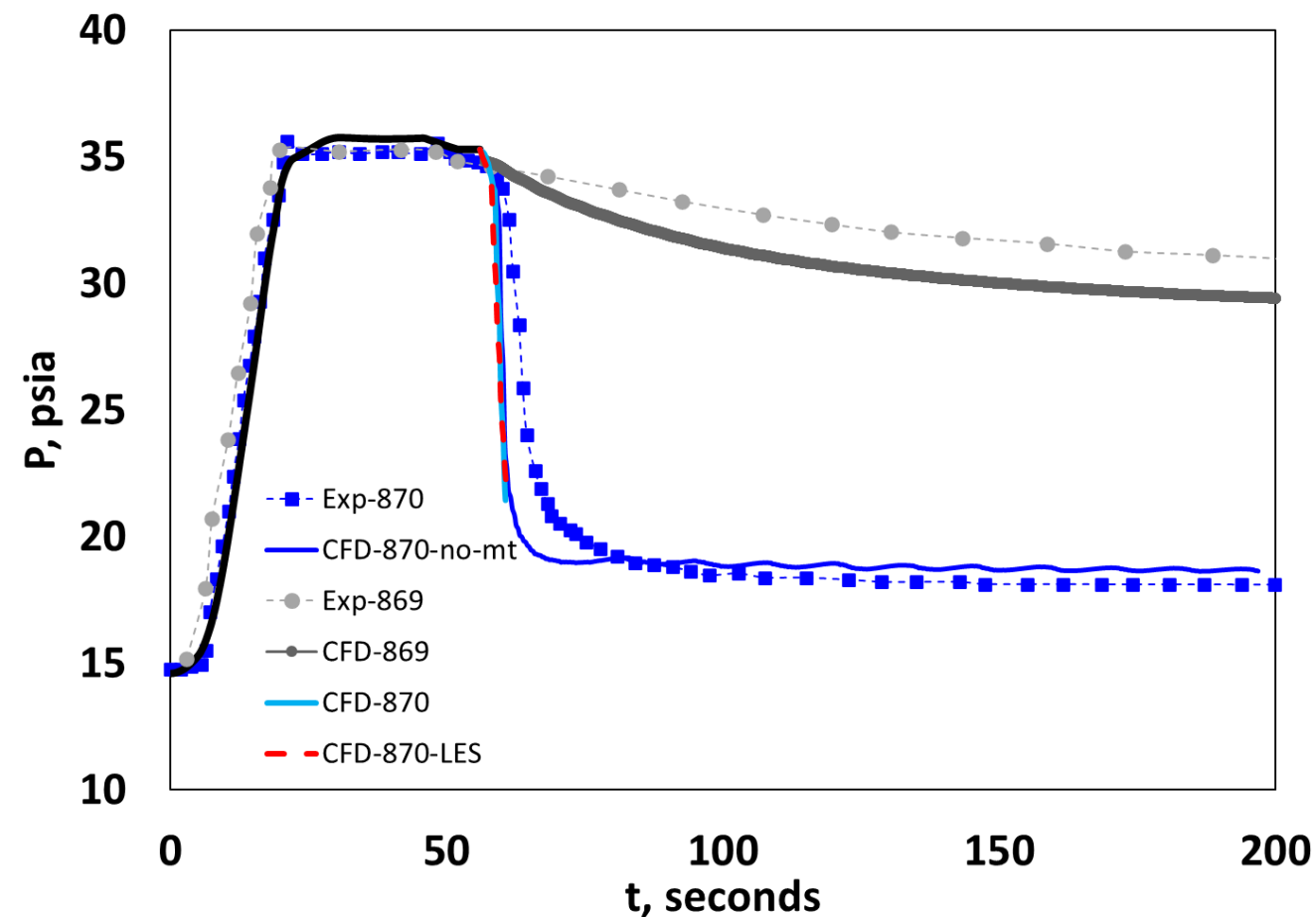


Fig. 6. Injected pressurant mass flow as a function of time for a liquid hydrogen slosh test.

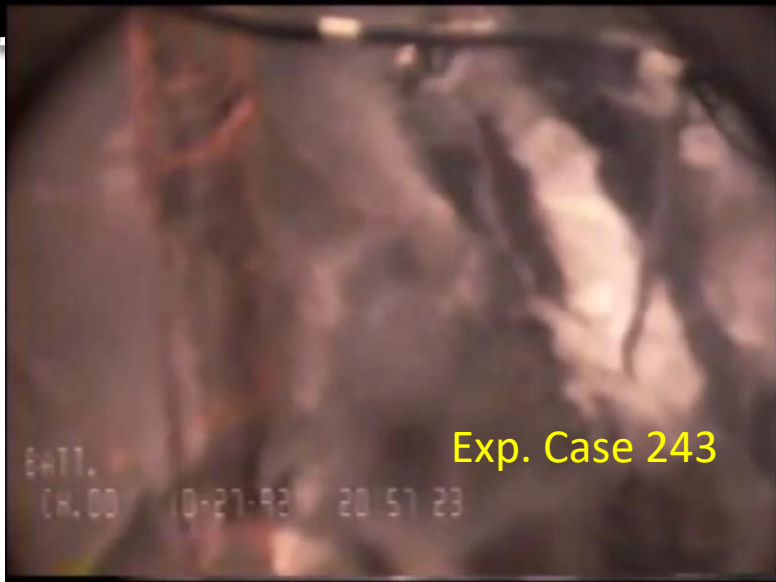


The Ground-Based K-Site Hydrogen Slosh Experiment – Sloshing



Test Case	Freq&Ampl	Ullage Volume, %	Pressure Collapse, %
869	0.95Hz; 0.5 ±in	33	29
870	0.74Hz; 1.5 ±in	36	84

CFD Results - Sloshing



Exp. Case 243

Test Case	Freq&Ampl	Ullage Volume, %	Pressure Collapse, %
869	0.95Hz; 0.5 ±in	33	29
242	0.95Hz; 0.5 ±in	49	30
870	0.74Hz; 1.5 ±in	36	84
243	0.74Hz; 1.5 ±in	49	68



Exp. Case 242

Case 870 – fine mesh, no MT

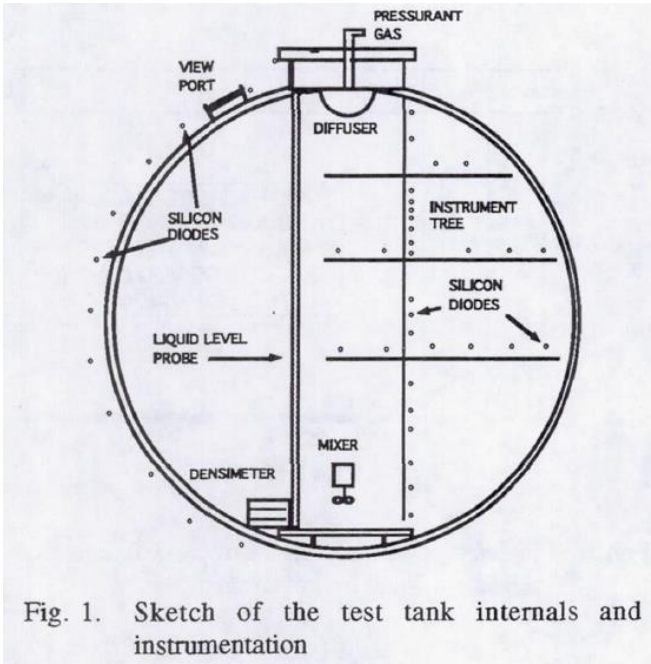
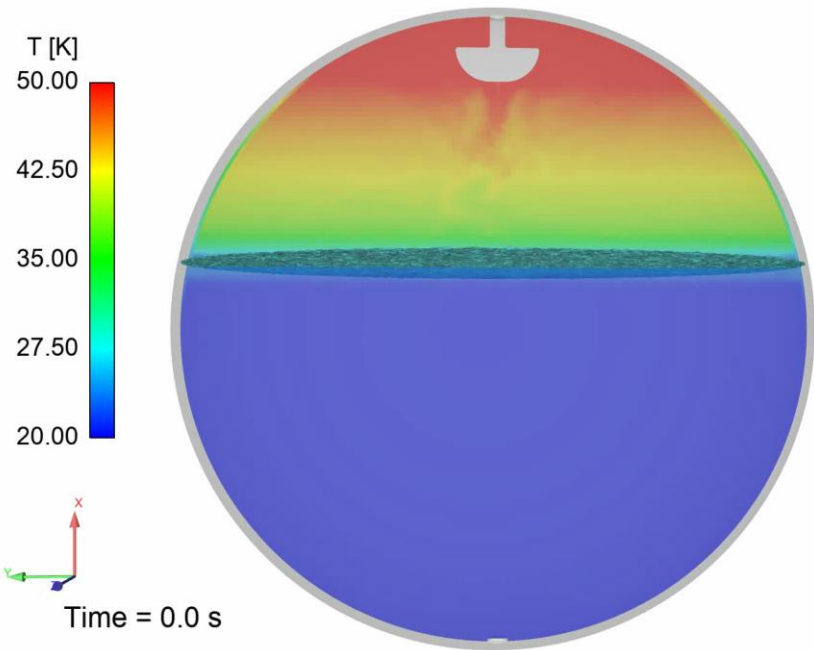
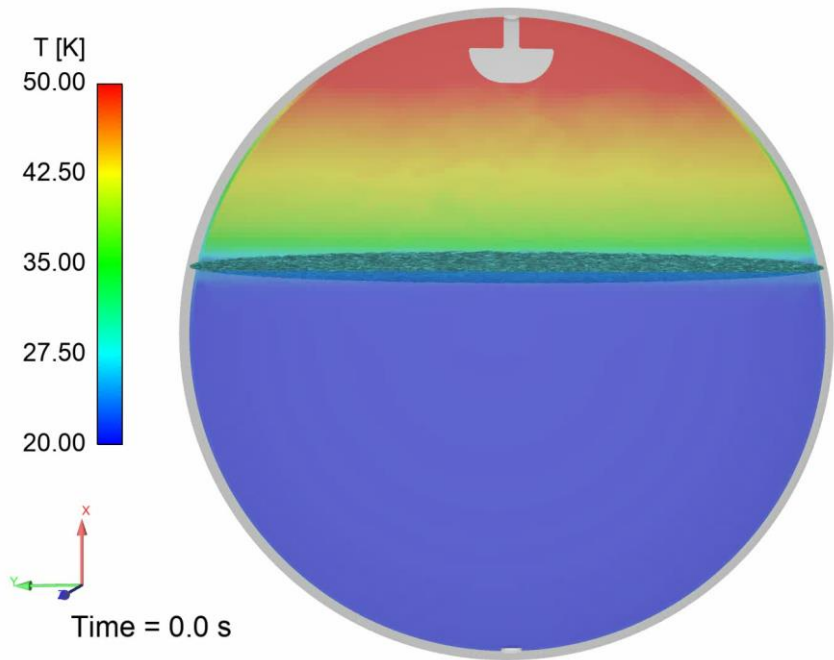


Fig. 1. Sketch of the test tank internals and instrumentation

Case 869 – fine mesh, with MT



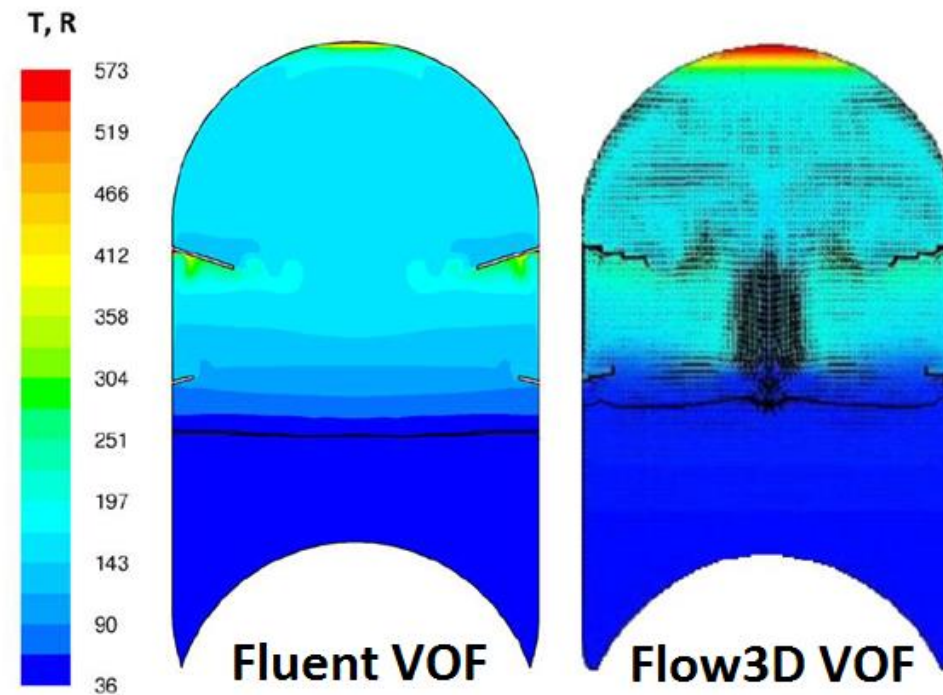


**Propellant Tank Self-Pressurization &
Pressure Control:
Microgravity Experiments and Model
Simulation**

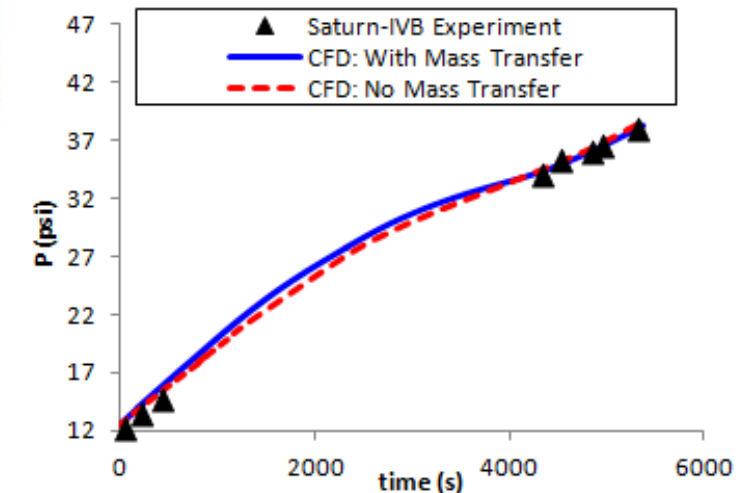
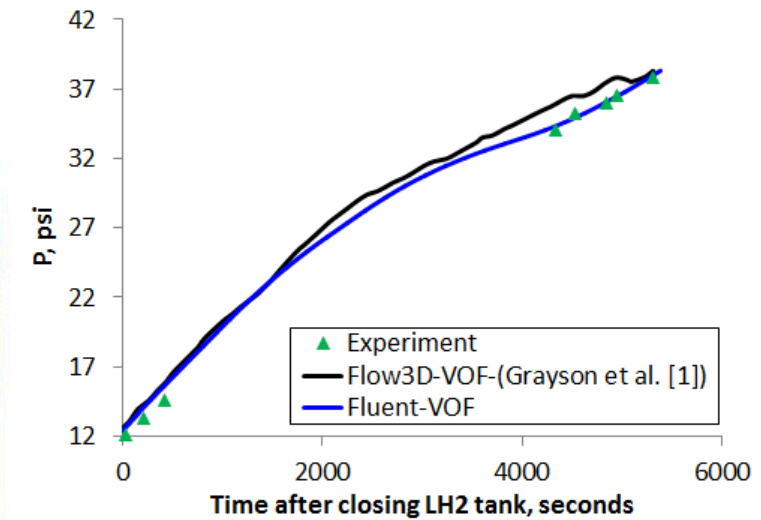
Saturn- IVB: Microgravity Tank Self-Pressurization

- Self-pressurization in Saturn-IVB LH2 tank during the AS-203 flight experiment, 1966
- Large scale tank (R = 3.3 m, height = 11.3 m)
- Liquid Hydrogen and Hydrogen Vapor
- Fill level is 32%
- Time-varying gravity conditions ($3.7\text{e-}4$ to $8\text{e-}5$ g)
- $Bo = 145$ to 43.5 (continuous LO2 ullage thrusters)
- Spatially-varying heat input (based on flight data)
- Average wall heat flux $q_w = 147 \text{ W/m}^2$
- 19.722 K uniform initial liquid temperature
- 2.44 K initial ullage stratification

Liquid remains essentially settled configuration (flat) for the entire duration of the self-pressurization portion of the test flight

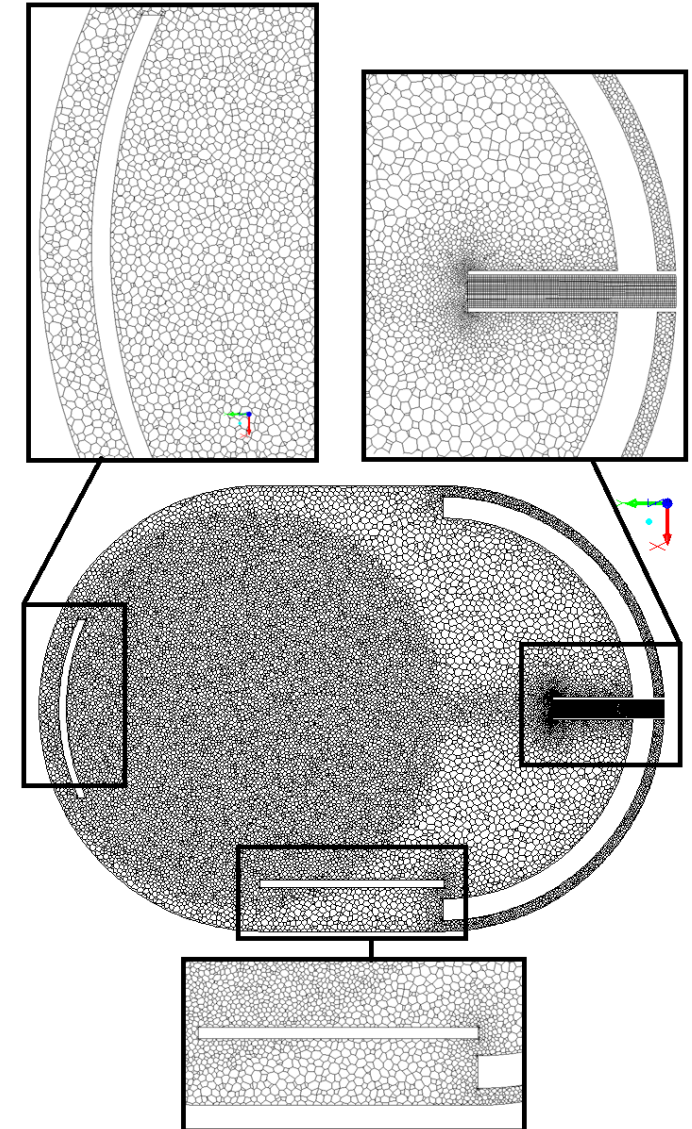
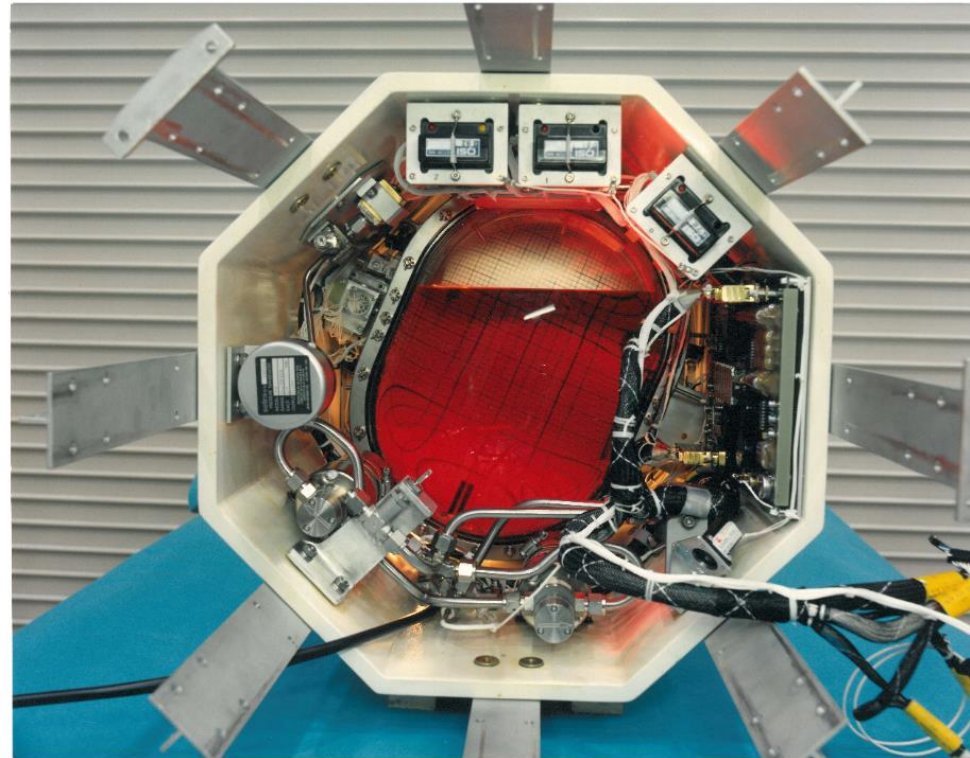
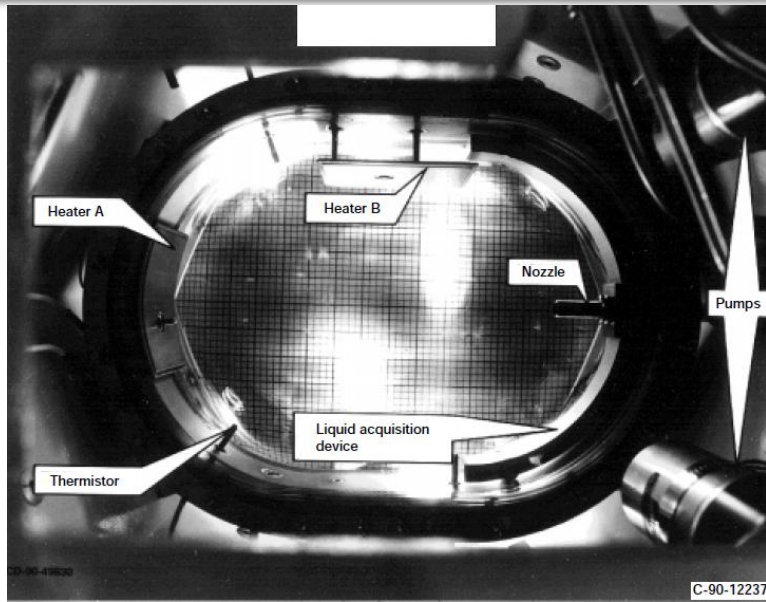


Mass transfer at liquid/ullage interface little effect on pressure rise for this experiment due to the relatively large wall heat fluxes along the S-IVB LH2 tank. Thus, this test data is not that useful for validation of mass transfer modeling.



[1] Grayson, G.D., Lopez, A., Chandler, F.O., Hastings L.J., Tucker, S.P., "Cryogenic Tank Modeling for the Saturn AS-203 Experiment," *Proceedings of the 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, AIAA 2006-5258, 2006 (4000 Cartesian cells mesh, "Model F")

Tank Pressure Control Experiment (TCPE)

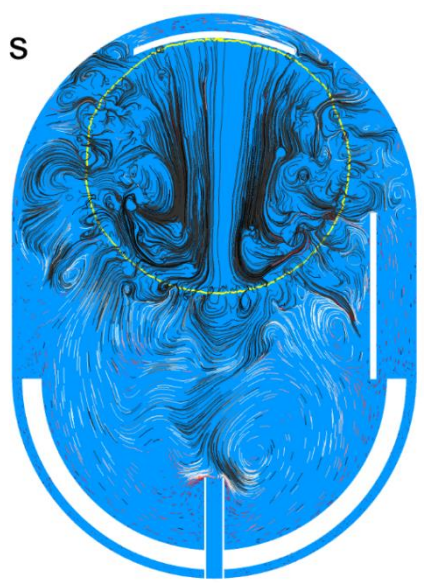
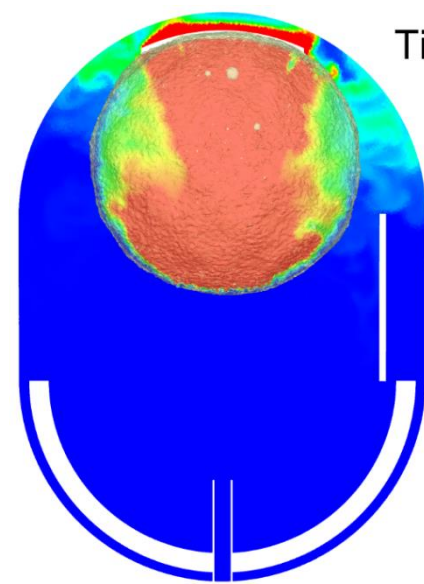
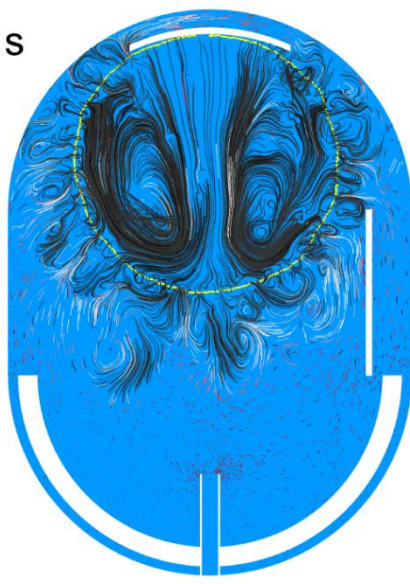
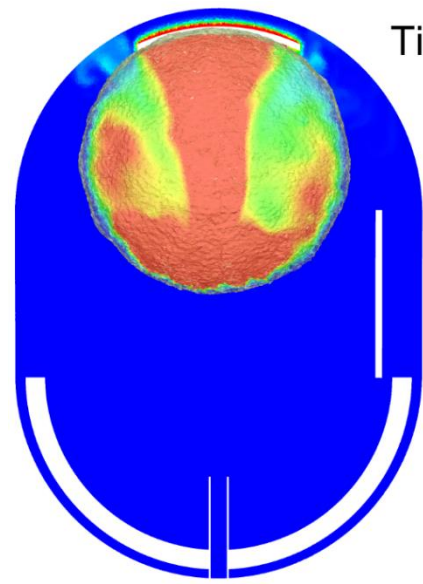
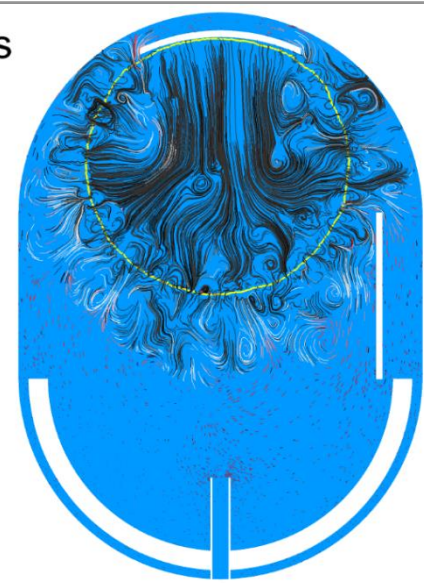
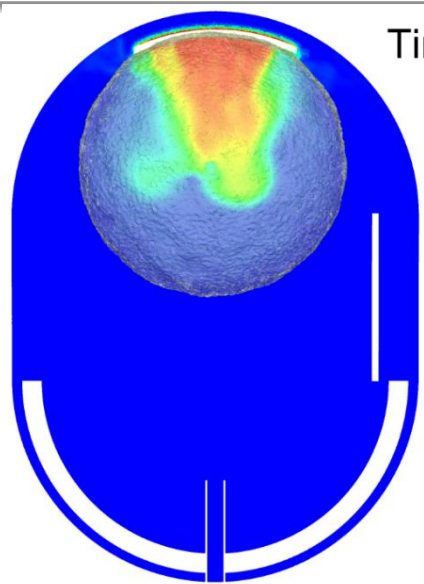
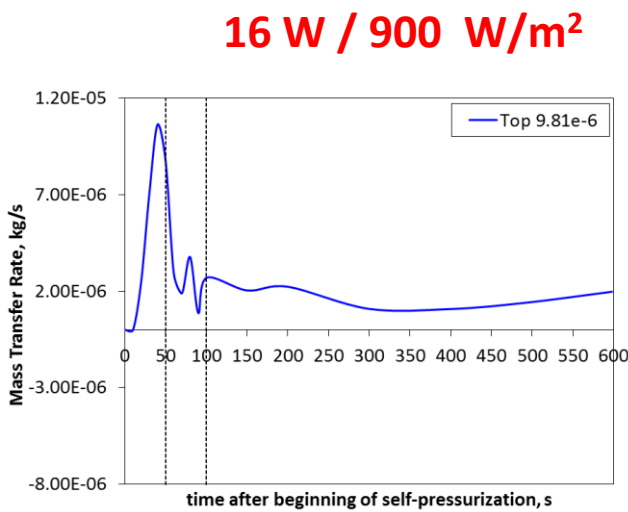
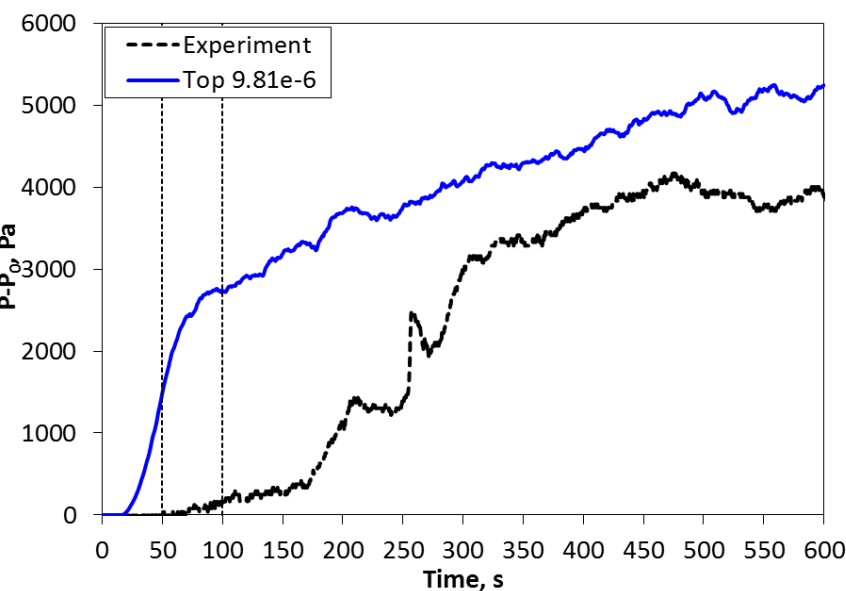


- Filled with **Freon-113**: **83% liquid fill** for Shuttles flights 1 (STS-43, 1991) and 2 (STS-52, 1992). 39% liquid fill for 3rd Shuttle flight..
- **25.4 cm** (10 in) diameter by **35.56 cm** (14 in) long cylindrical tank with hemispherical domes was constructed of transparent acrylic plastic

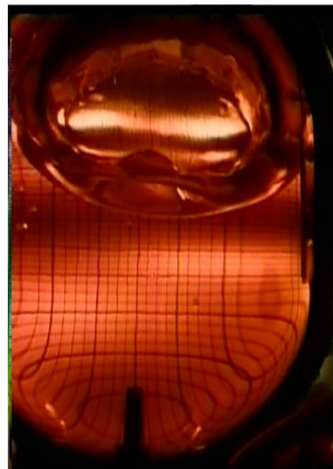
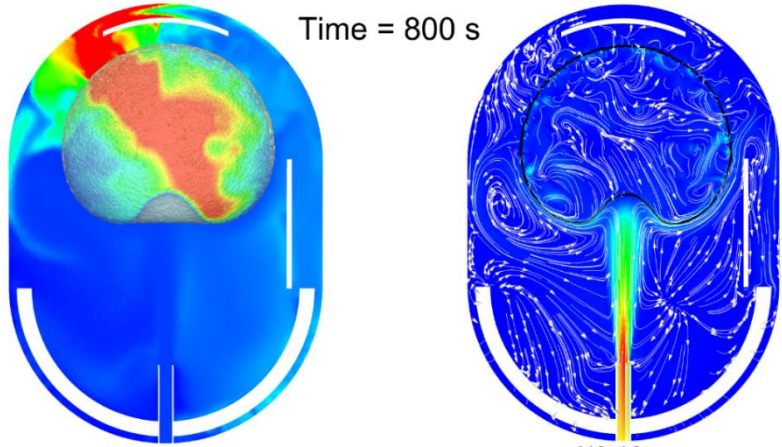
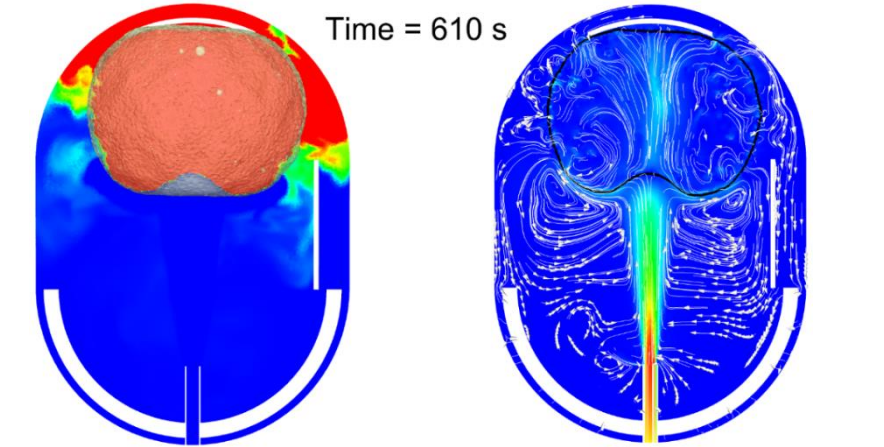
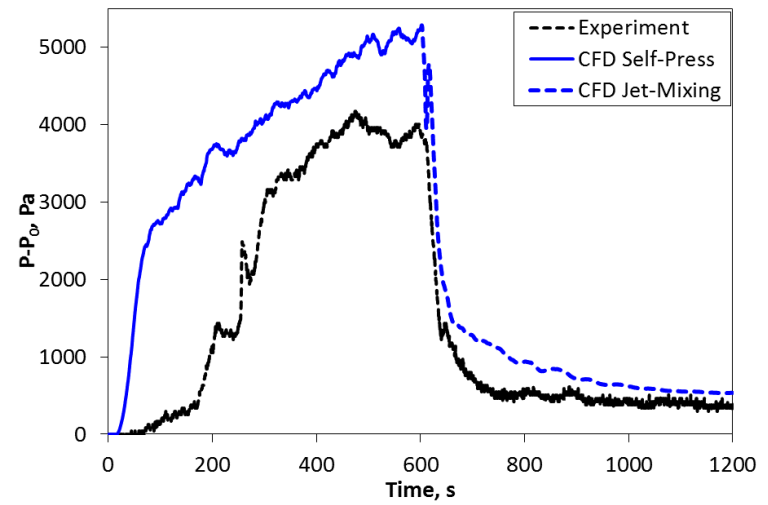
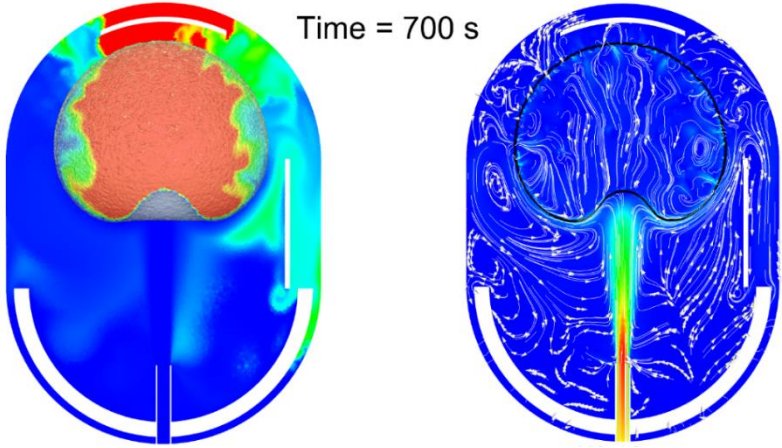
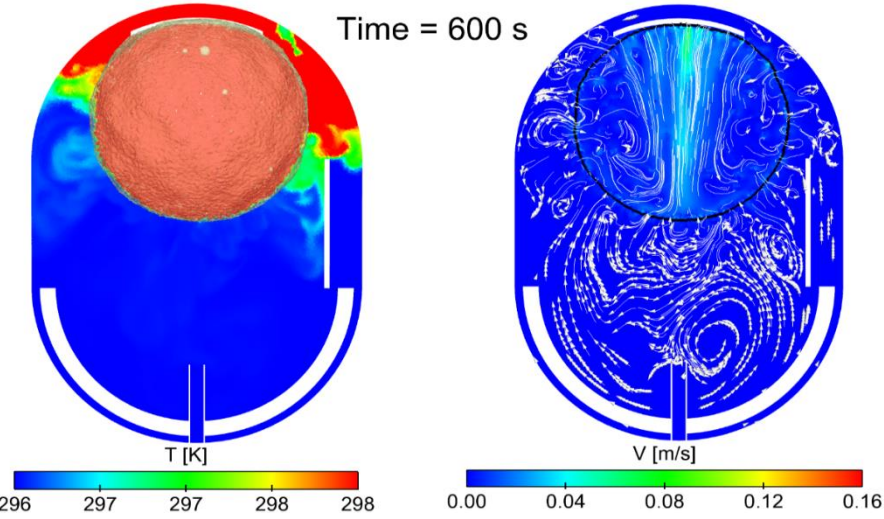
TPCE Test Tank inside the
Getaway Special Container

1,505,726 polyhedral cells

Fluent Simulations of TPCE Microgravity Self- Pressurization

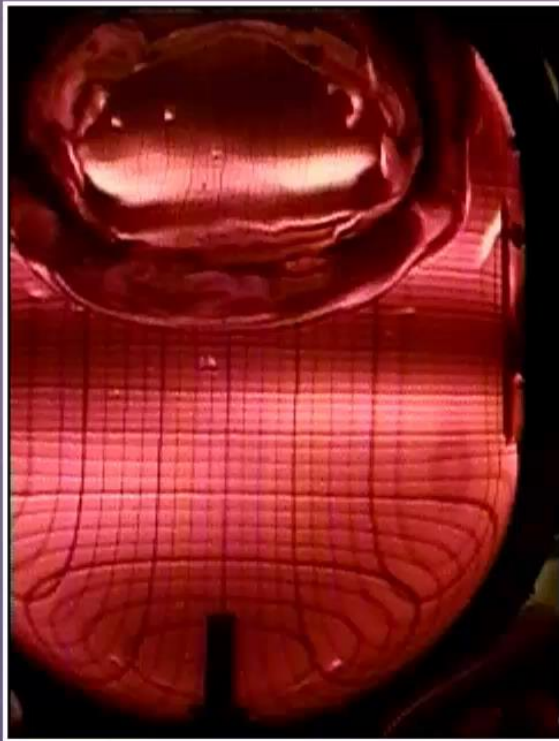


Fluent Simulations of TPCE Microgravity Jet Mixing Pressure Control

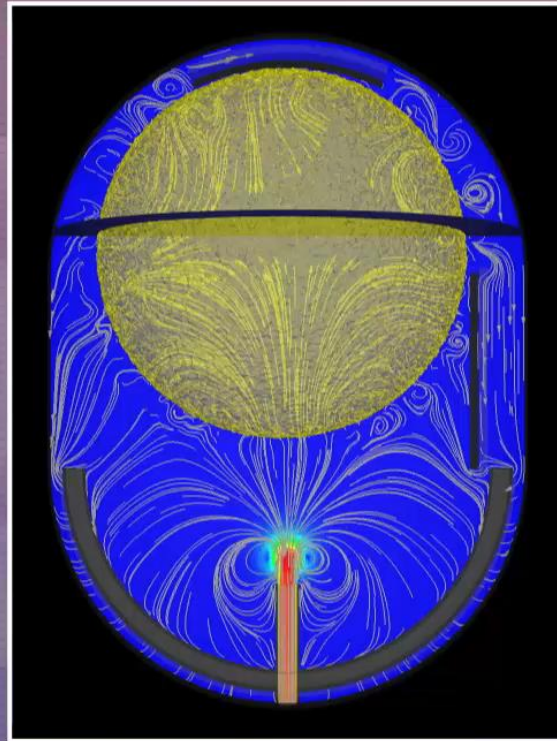


Weber Number	0.71
Flow rate l/min	0.59
Jet Velocity m/s	0.12

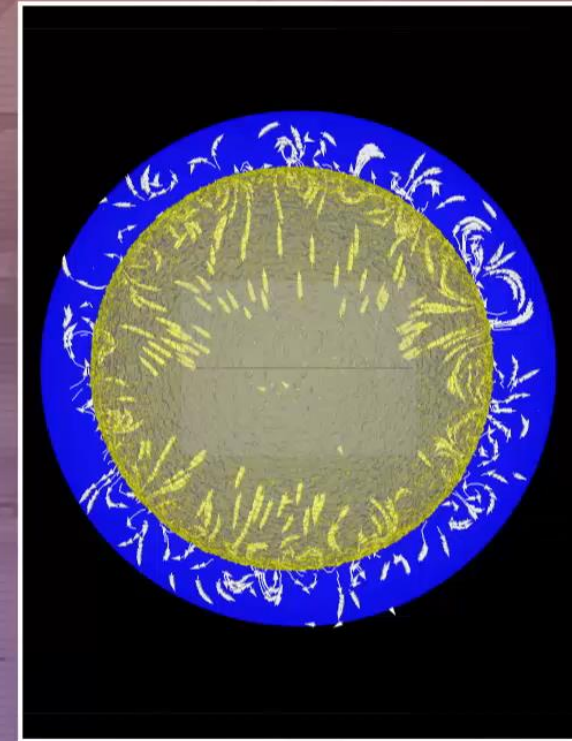
Tank Pressure Control Experiment (TPCE) Small Scale, Simulant Fluid, Microgravity: STS-43, 1991



TPCE: Experiment



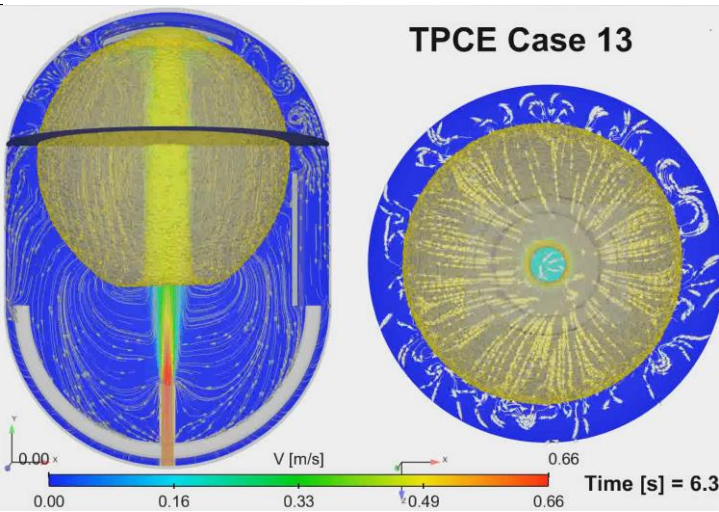
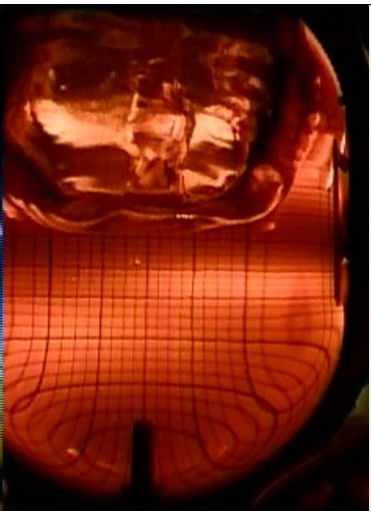
NASA GRC CFD Simulation
(Front View)



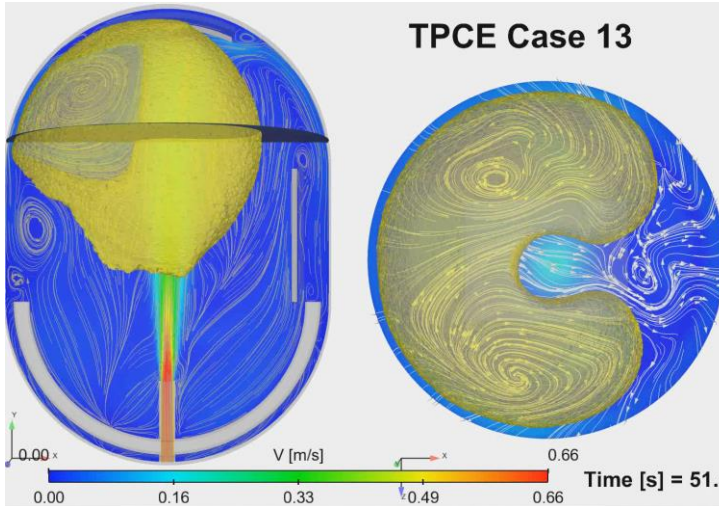
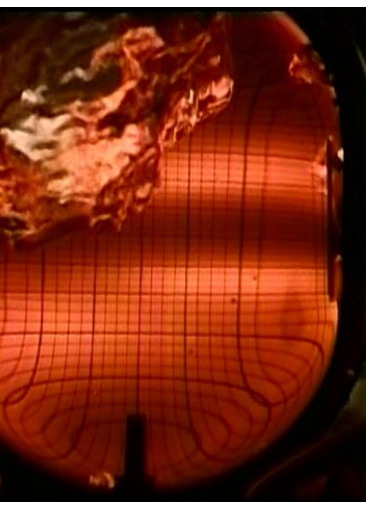
NASA GRC CFD Simulation
(Cross-sectional View)

Case 13: Weber number = 15.55, Jet Velocity = 0.57 m/s

Fluent Simulations of Microgravity TPCE Test Run 13 - Isothermal Mixing & Jet-Ullage Penetration



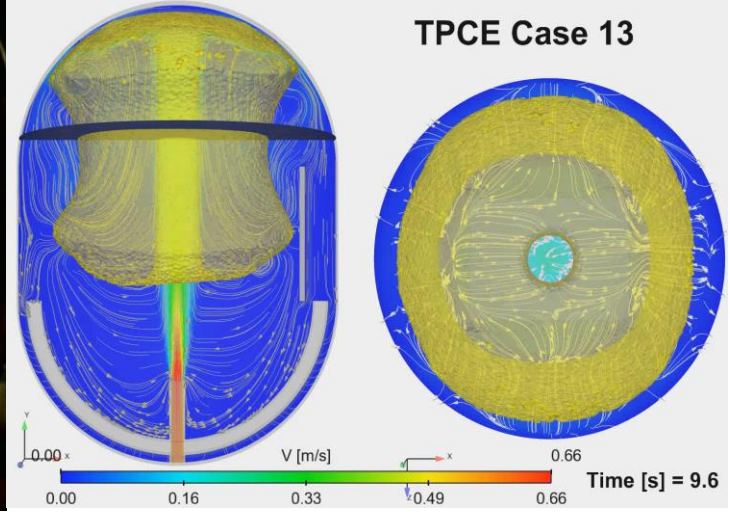
Sequence A (6.3 s): tubular flow penetrating the ullage along the central axis



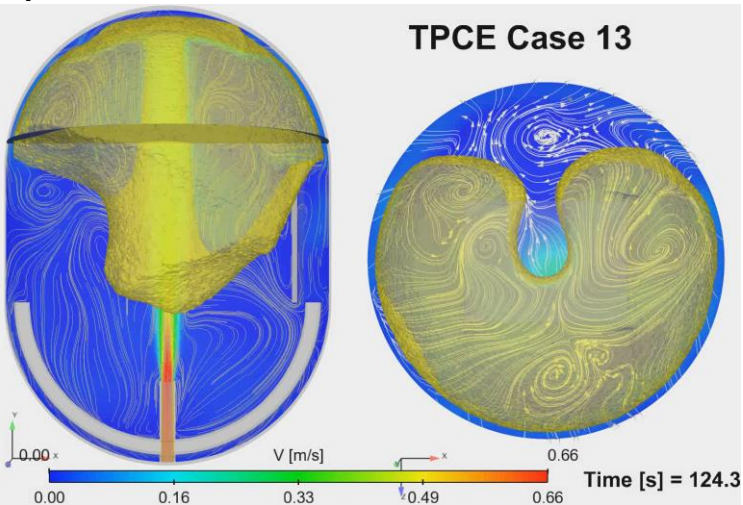
Sequence C (51.3 s): jet penetration becomes asymmetrical moving the ullage away from the side heater

Jet Mixing
Without
Heat & Mass
Transfer

Weber Number	15.6
Flow rate l/min	2.78
Jet Velocity m/s	0.57



Sequence A (9.6 s): elongating of the ullage along the central axis creates “apple core” shape



Sequence C (124.3 s): rotation of the ullage results in elongated asymmetrical ullage shape

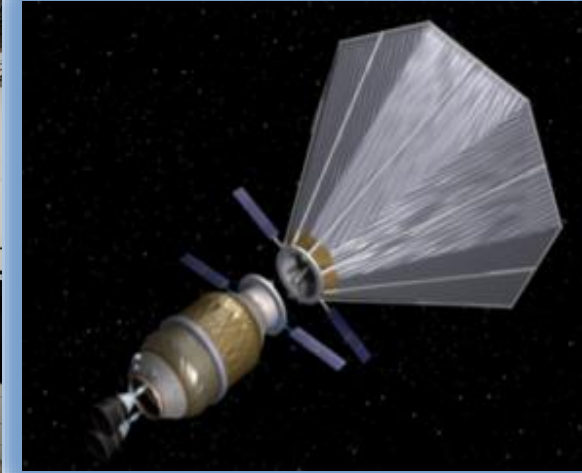


The ZBOT Microgravity Experiments

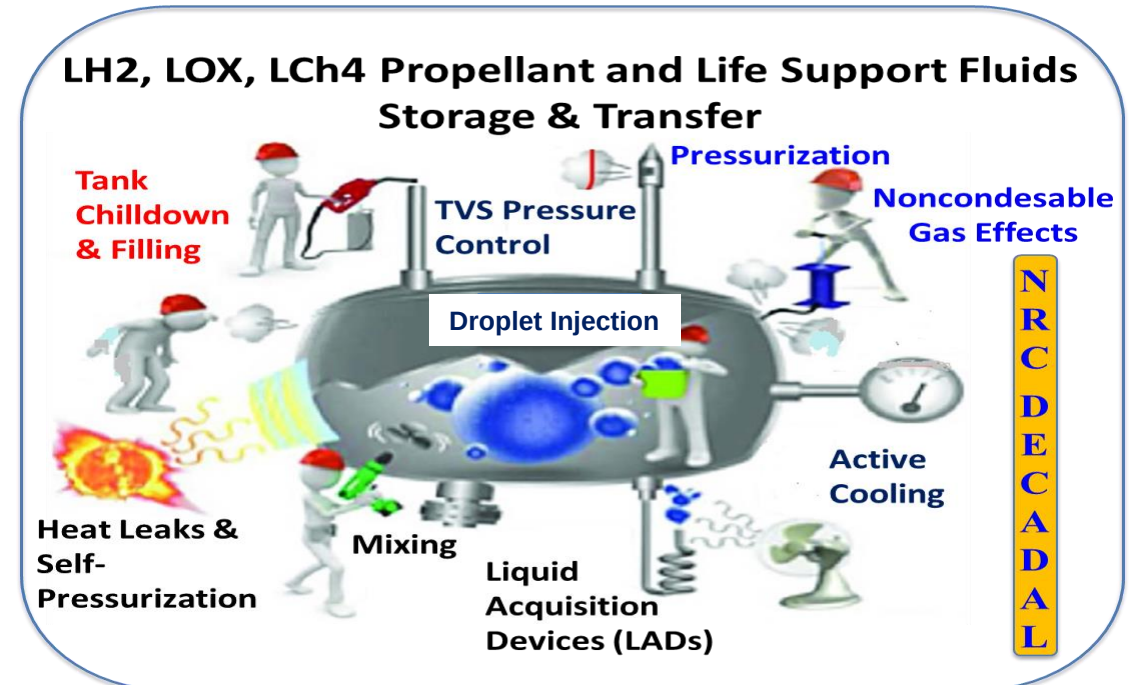
Zero Boil-Off Tank (ZBOT) Experiments



- Feasibility of imminent Lunar & future Mars Missions depend largely on successful implementation of ZBO Cryogenic Tank Pressure Control for propellant storage & transfer.
- ZBO brings significant cost saving through payload mass reduction but is complicated to design due to complex microgravity two phase fluid/heat transfer.
- The Zero Boil Off Tank (ZBOT) Experiments use small-scale *simulant*-fluid tests aboard the ISS and hand-in-hand development of a two-phase CFD model to study the underlying fluid physics of tank pressurization & pressure control in order to optimize in-orbit propellant storage & transfer processes.

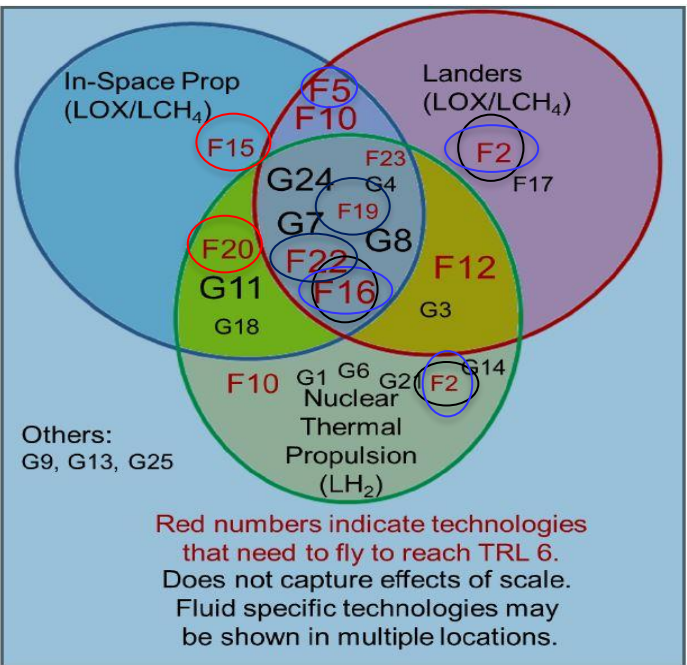


- **ZBOT-1: Self-Pressurization & Jet Mixing (2017)**
 - Self-Pressurization, Thermal stratification, 0G boiling
 - Jet Mixing/Cooling, Thermal destratification, Ullage-Jet dynamics
- **ZBOT-NC: Effect of Non-Condensable Gases (2022)**
 - NC effect on self-pressurization / stratification
 - NC effect on pressure control / destratification
 - Condensation suppression, Marangoni convection
- **ZBOT-DP: Spray Cooling Pressure Control /Tank Chillover (2025)**
 - Droplet Spray Bar (TVS) Cooling
 - Tank Chillover
- **ZBOT-FT: Filling & Transfer (German UoB-DLR Collaboration)**
 - Tank-to-Tank Transfer

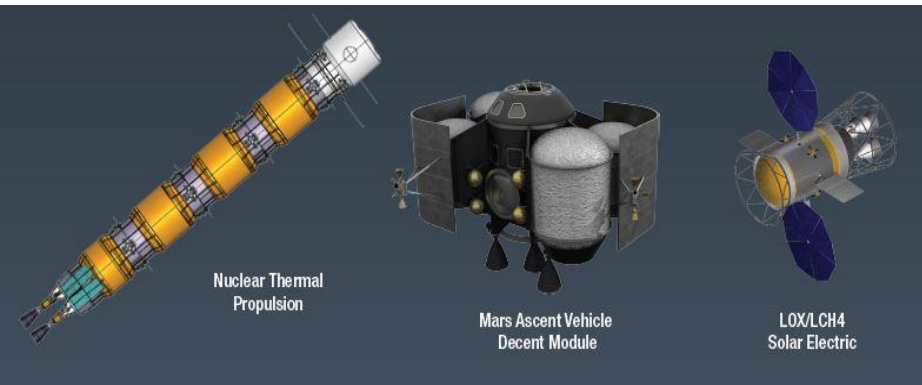


Roadmap for CFM Tech Needs Across Mission Architectures

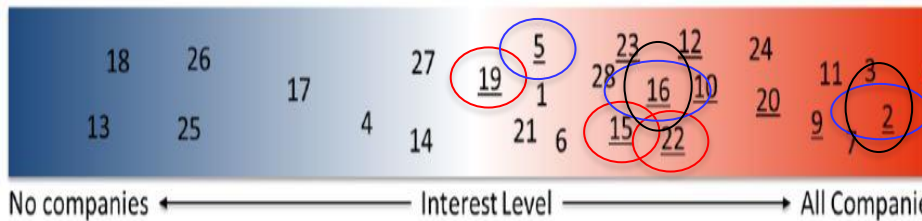
CFM Tech across Multiple Architecture



Mission Architecture



Heat Map of Industry Interest



Required CFM Technology Elements

Technology	No
Advanced External Insulation	1
Autogenous Pressurization	2
Automated Cryo-Couplers	3
Cryogenic Thermal Coating	4
Helium Pressurization	5
High Capacity, High Efficiency Cryocoolers 20K	6
High Capacity, High Efficiency Cryocoolers 90K	7
High Vacuum Multilayer Insulation	8
Liquefaction Operations (MAV & ISRU)	9
Liquid Acquisition Devices	10
Low Conductivity Structures	11
MPS Line Chilldown	12
Para to Ortho Cooling	13
Propellant Densification	14
Propellant Tank Chilldown	15
Pump Based Mixing	16
Soft Vacuum Insulation	17
Structural Heat Load Reduction	18
Thermodynamic Vent System	19
Transfer Operations	20
Tube-On-Shield BAC	21
Tube-On-Tank BAC	22
Unsettled Liquid Mass Gauging	23
Valves, Actuators & Components	24
Vapor Cooling	25

ZBOT-1

ZBOT-NC

ZBOT-NC

ZBOT-DP

ZBOT-FT

ZBOT-1

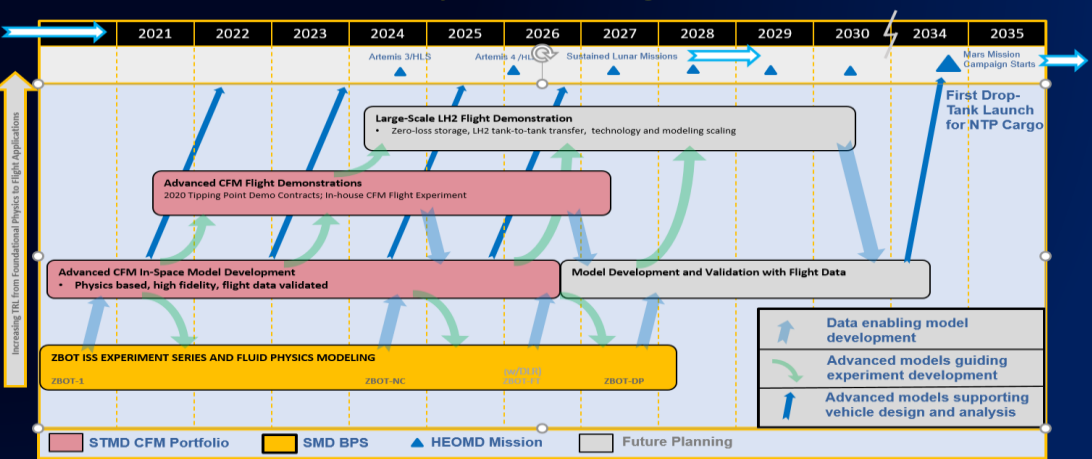
ZBOT-NC

ZBOT-DP

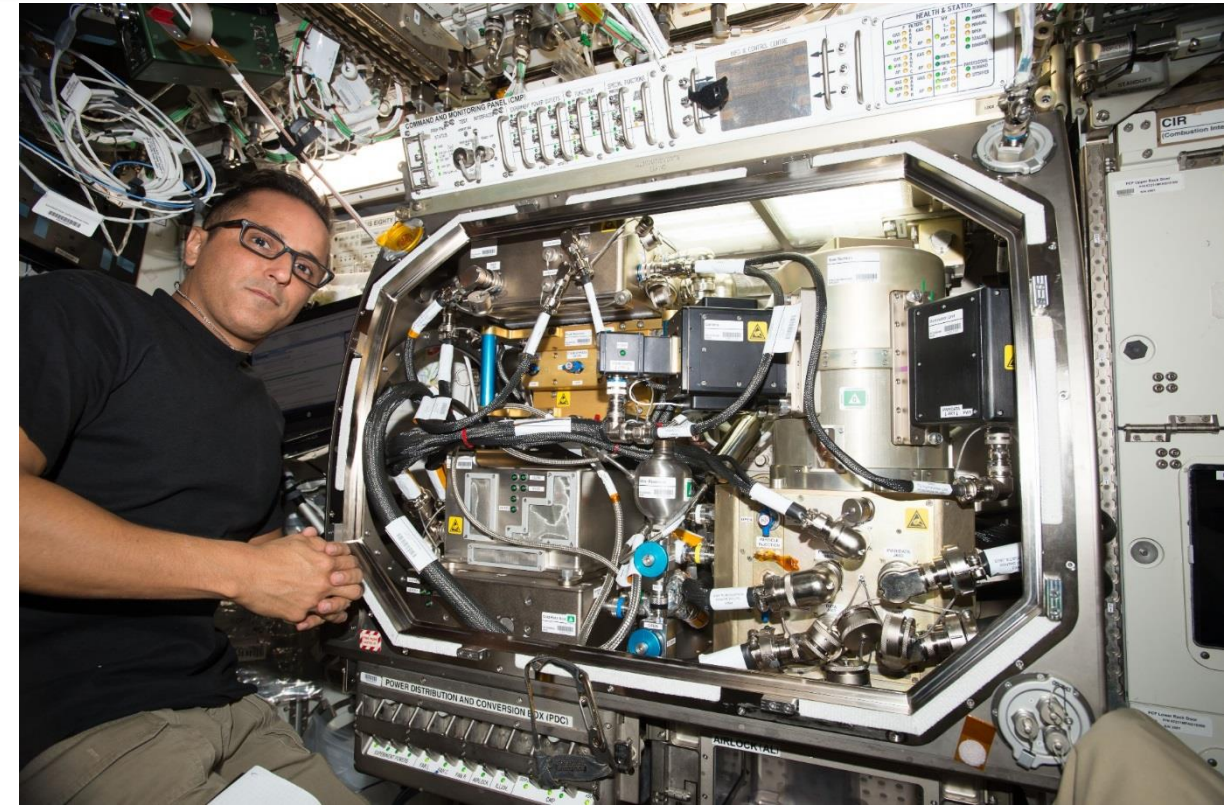
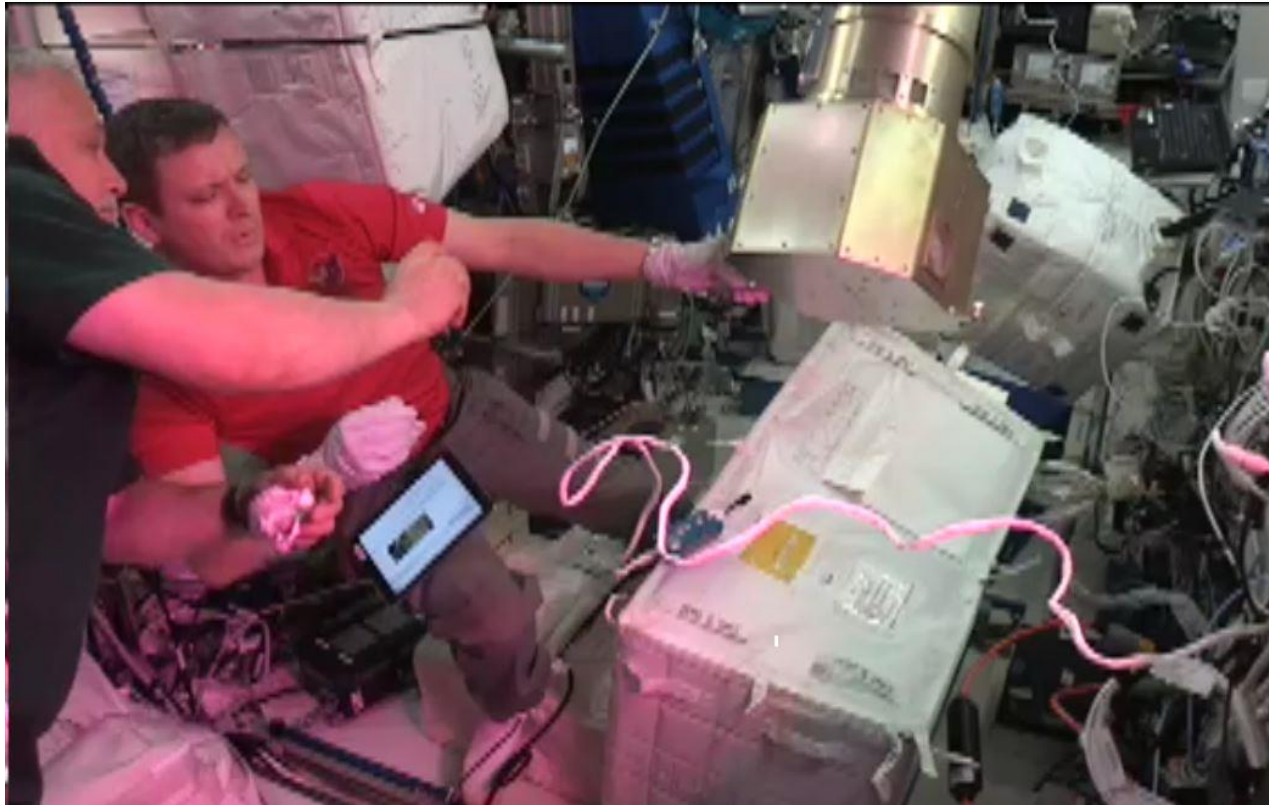
ZBOT-FT

ZBOT-DP

STMD Path from Foundational Physics to Enabling CFM for Crewed Missions



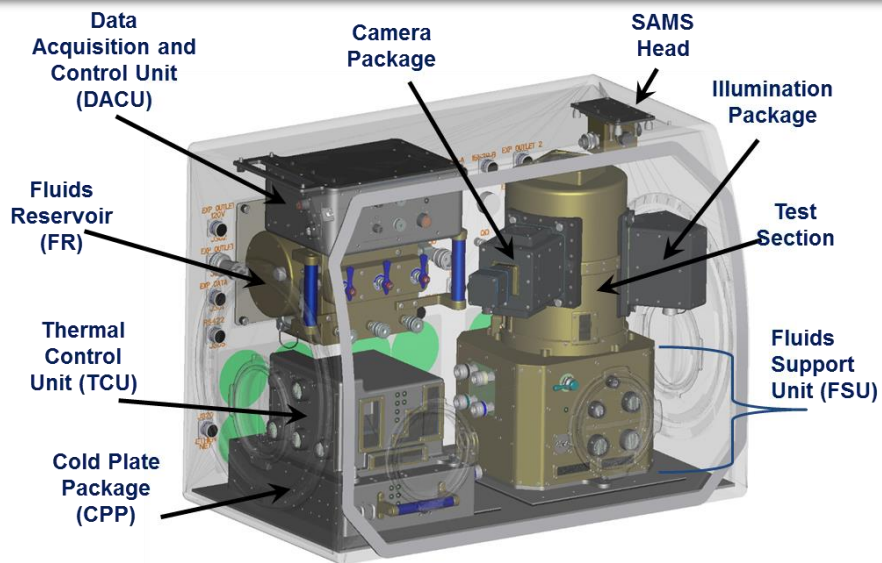
ZBOT-1 Hardware in MSG Aboard ISS



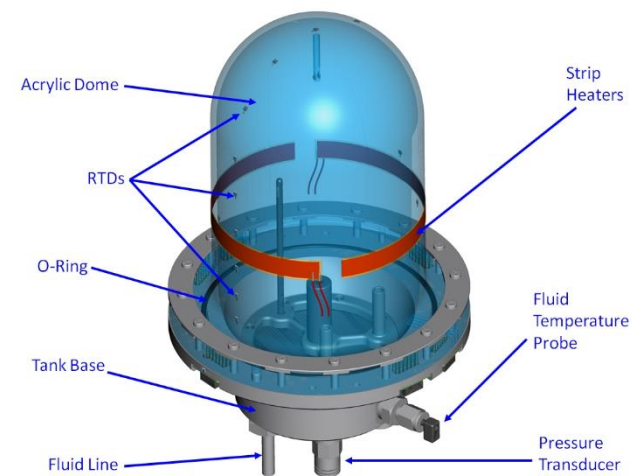
- Experiment was installed by Astronaut Joe Acaba on September 19 & 20th in the MSG and powered up.
- System thermal & fluid characterization started on September 24th
- Actual Test runs began on Oct 1st
- Over 100 test runs were conducted
- Data and images were downloaded continuously



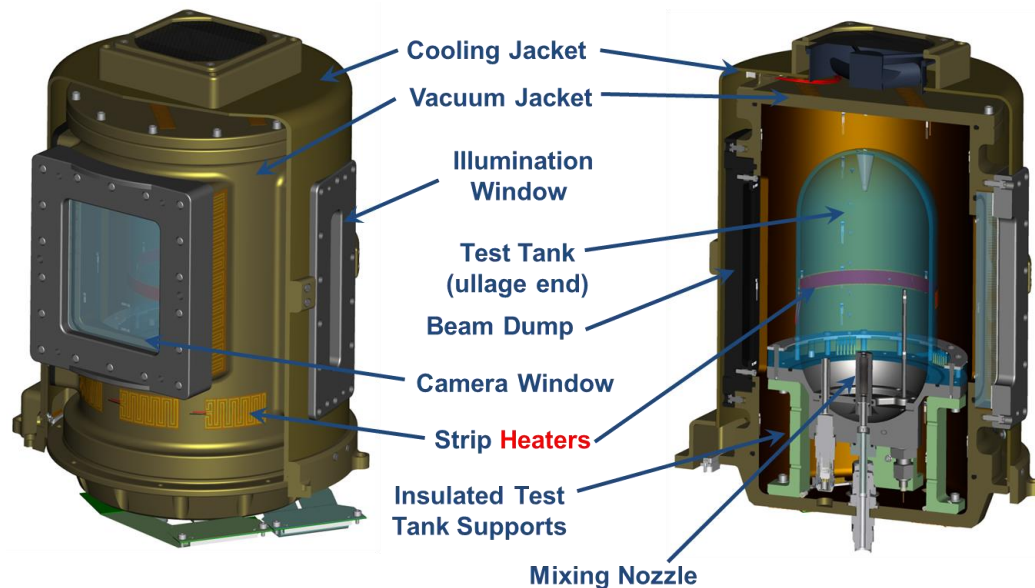
ZBOT-1 Hardware Components



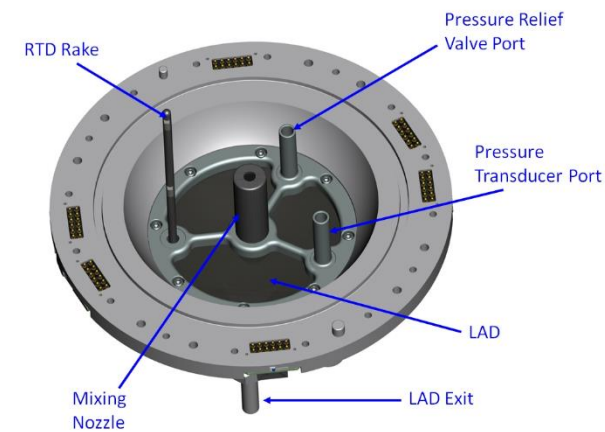
ZBOT Hardware Components in MSG



Acrylic Test Tank Dome

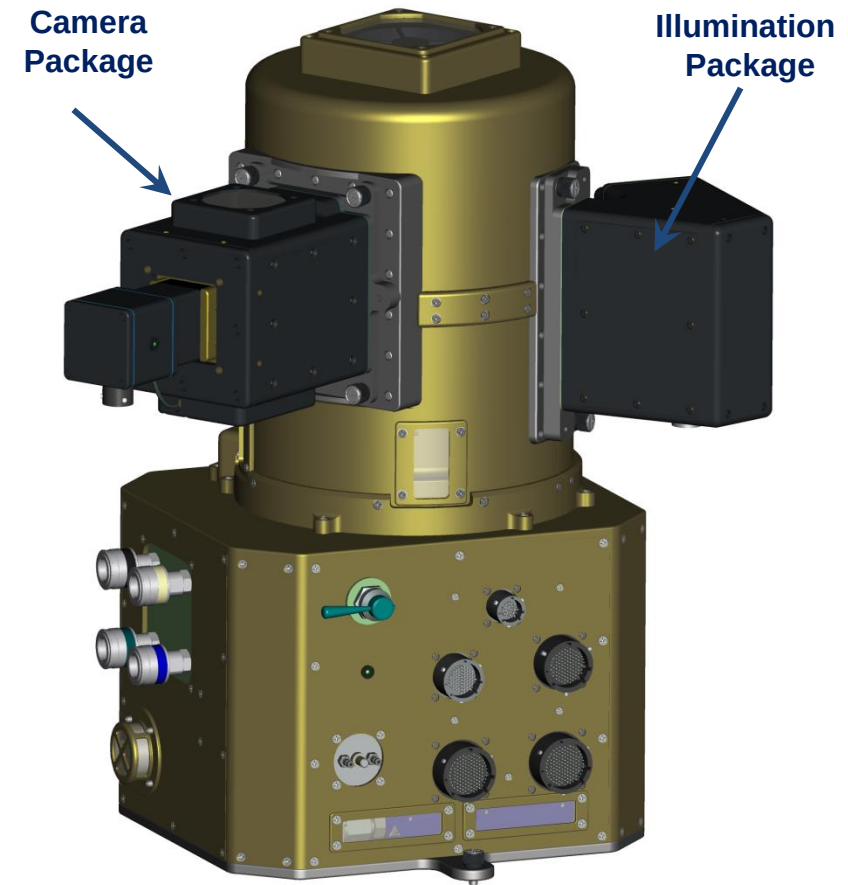
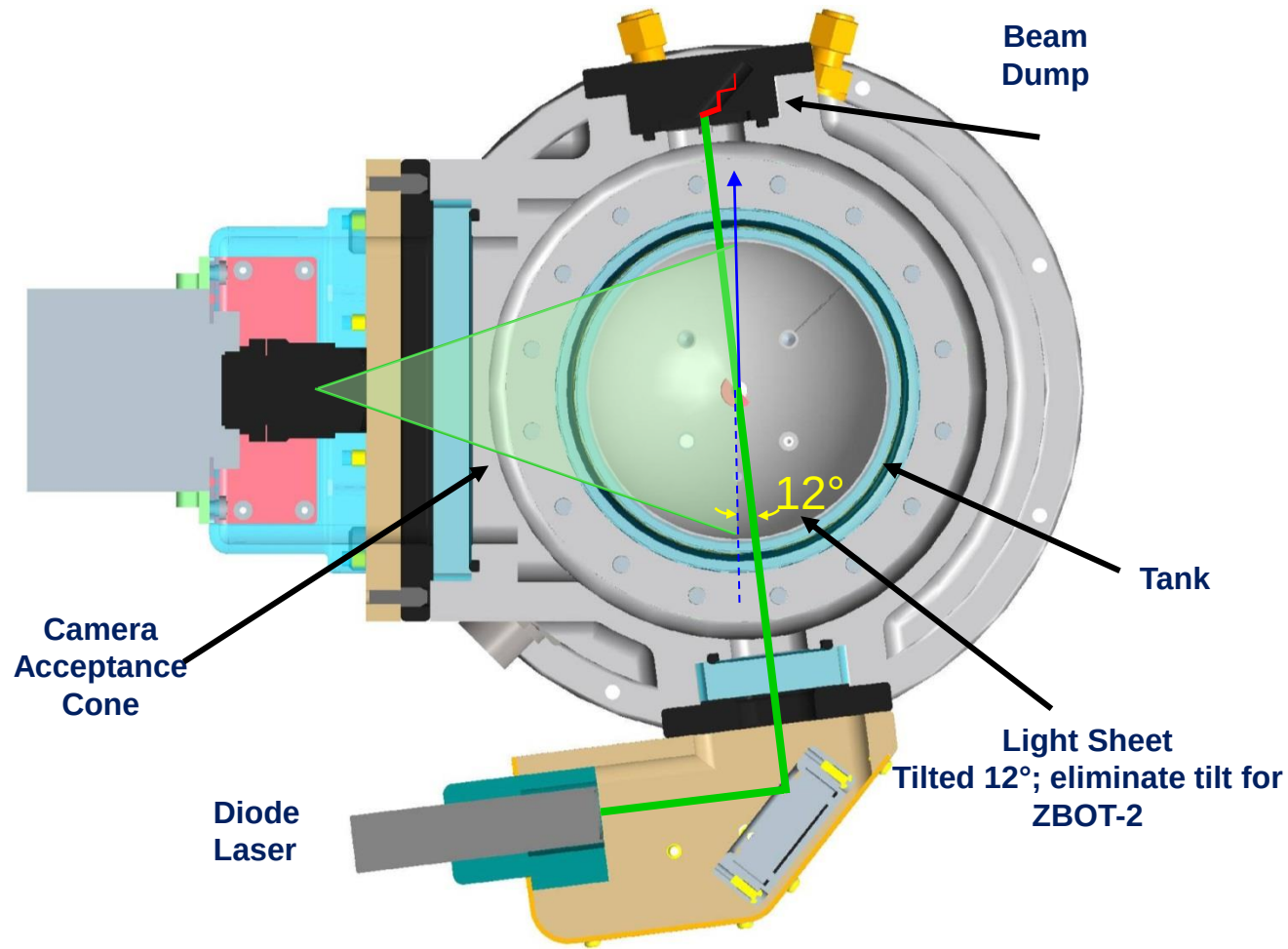


ZBOT Test Tank inside the Vacuum Jacket



Stainless Steel Test Tank Base, Nozzle & Screen LAD

ZBOT-1 Camera & Illumination Package for Image Capture & PIV



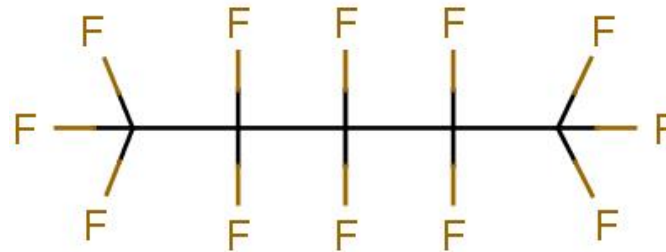
ZBOT-1 Tank Pressurization & Mixing Cooling Test Matrix



- Refrigerant
- High purity (99.7% straight-chained n-isomer)
- Boiling Point = 29°C @ 1 atm
- Vapor Pressure = 12.5 psia @ 25°C
- Near zero contact angle with test tank

Perfluoro-n-Pentane

(PnP, or C5F12) n-Isomer (Straight Chained) Chemical Structure



- ~ 70 pressurization, jet mixing, and destratification tests were performed first at 3 fill levels with and without Particle Imaging Velocimetry (PIV)
- ~ 20 Tests were conducted with particles injected & PIV performed as Tech Validation
- Currently 30 model validation cases identified

Type of Test	Method & Mode
Pressurization	Heater Strip
	Vacuum Jacket Heating
	Heater and Vacuum Jacket
Mixing Only	Uniform Temperature
	After Self-Pressurization
Subcooled Mixing	Uniform Temperature
	After Self-Pressurization

Input Variables (Tolerances)
Heater Power (w/ in 5 mW RMS)
Vacuum Jacket Offset (+/- 0.2°C)
Fill Level (70% +/- 3%, 80% +/- 3%, 90% -3%)
Jet Temperature (+/- 0.25°C)
Jet Velocity/Flow rate (10% of reading)

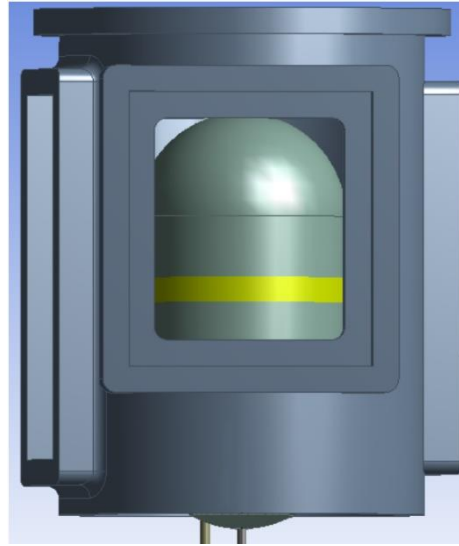
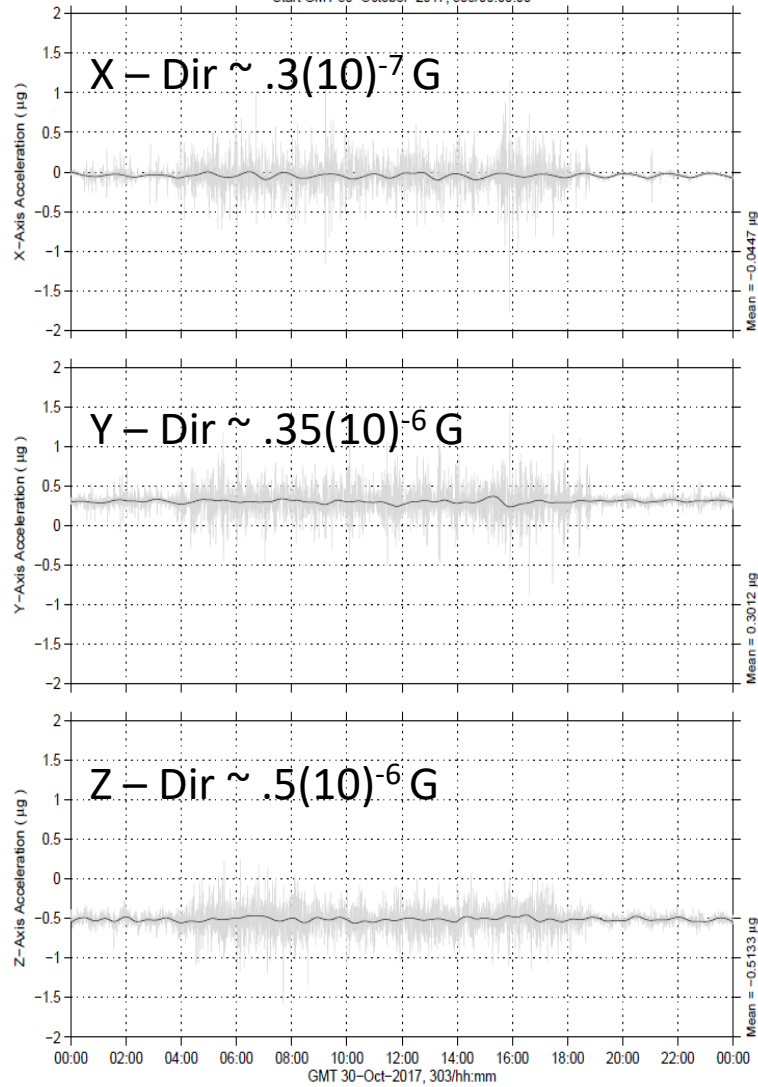
Outputs as Time Evolution
Pressure
Fluid Temperature (6 locations)
Wall Temperature (17 locations)
Jacket Temperature (21 locations)
Jet Penetration Depth
DPIV Velocity/Flow Structures

ZBOT Microgravity Residual Gravity Magnitude & Orientation



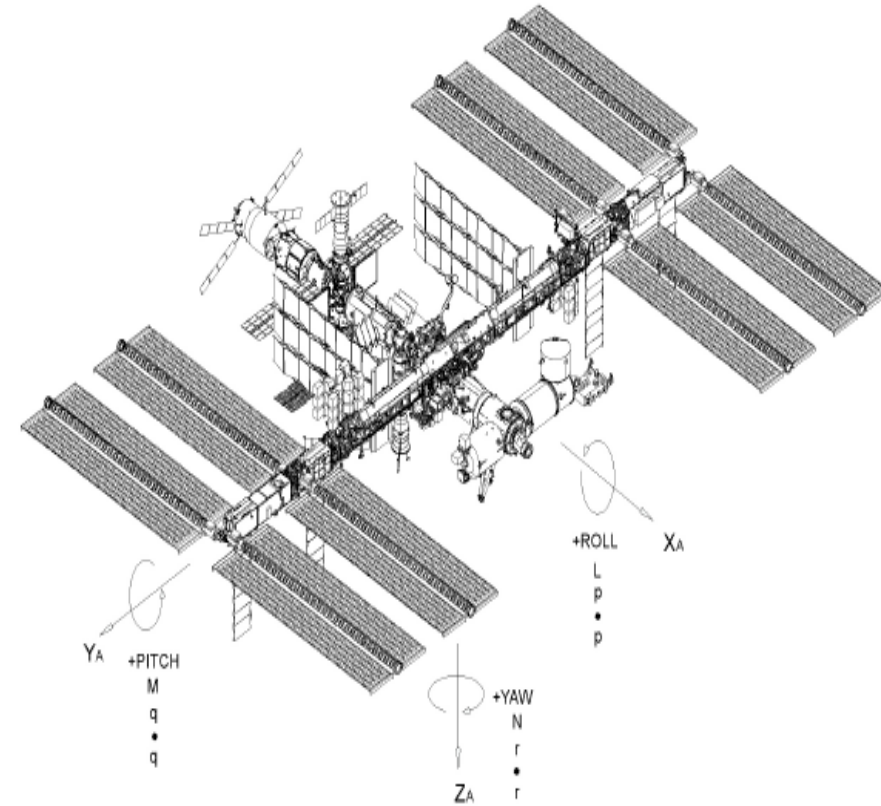
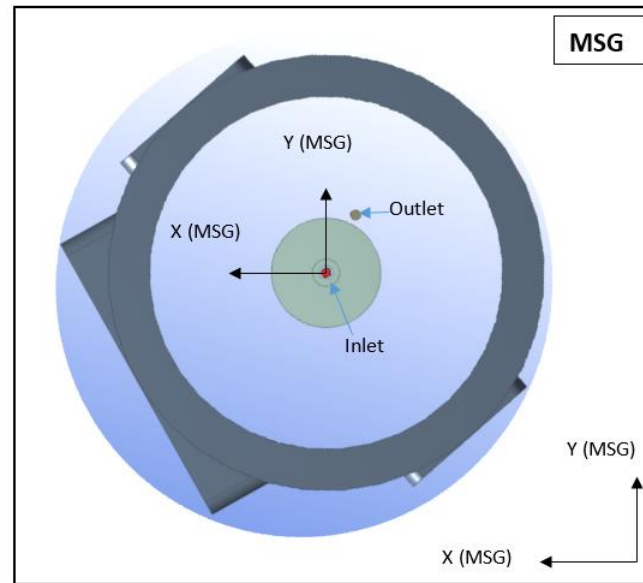
TIME-SHIFTED HISTORICAL MAMS DATA
FROM GMT 01-Nov-2015 05:16:48 TO 02-Nov-2015 05:16:48

Start GMT 30-October-2017, 303/00:00:00



Z MSG

+



Outline – Microgravity Results



1. Tank Self-Pressurization in μG

Similar to 1g - *We have good handle on it* 

2. Effect of Sudden Accelerations on Tank Pressurization

What accelerations are impactful?

3. μG Boiling at Hotspots During Self-Pressurization

Unlike 1G It Does not take much !! 

4. Microgravity Jet Mixing

Jet Ullage Interaction in μG is non-intuitive!!

5. Validation of Jet Mixing Results With PIV

Turbulence!!

6. Pressure Control with Subcooled jet mixing

Effective – ***But Surprise at the LAD***



Microgravity Self-Pressurization

Vacuum Jacket Self-Pressurization in Microgravity - Followed by Subcooled Jet Mixing



12 hrs 1f/30s

(#17) VJ Self Press (76%)

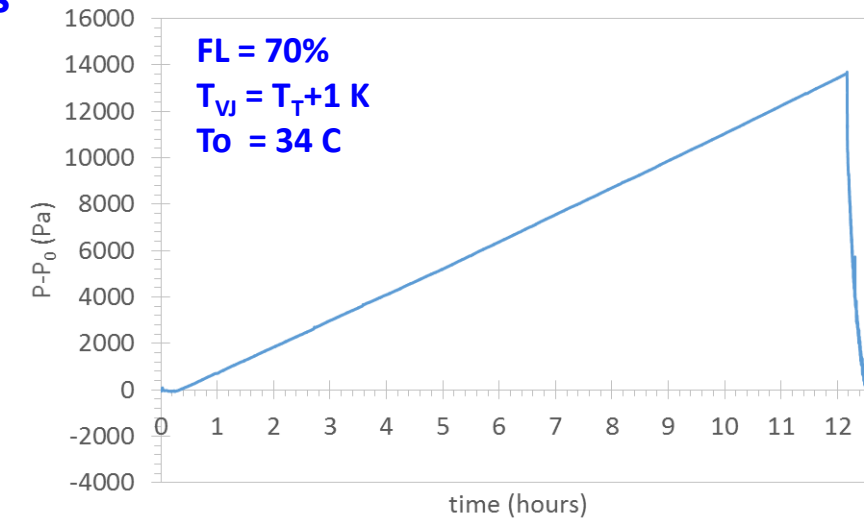


30 min 1f/2s

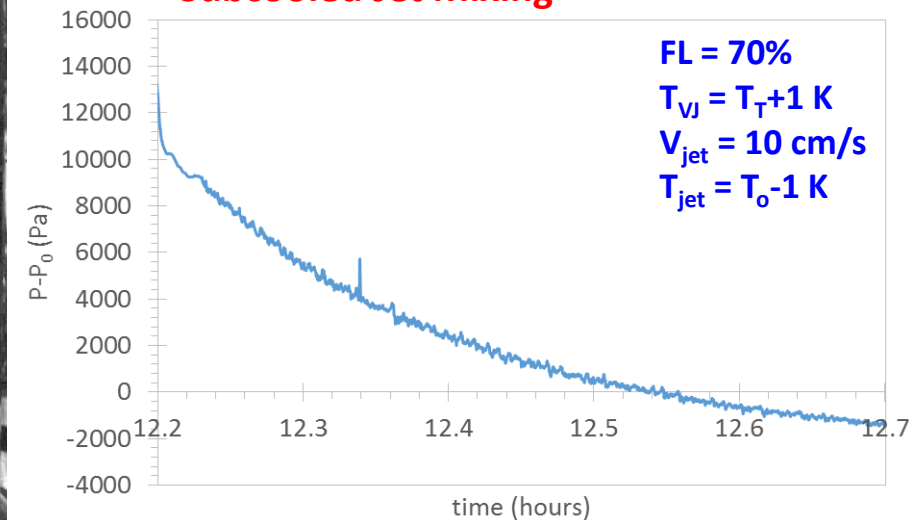
(#201) $T_o - 1$ K 10 cm/s SC Jet after Self-Press



VJ Self-Pressurization



Subcooled Jet Mixing

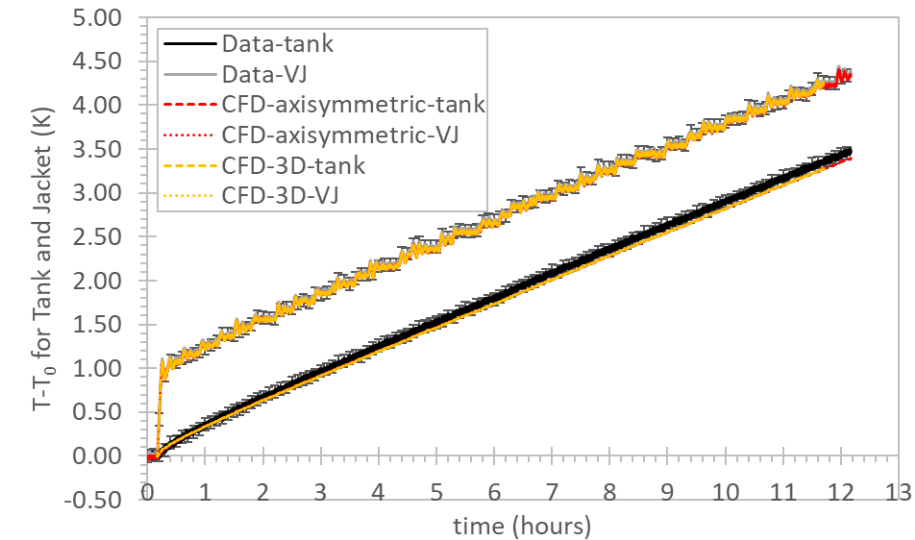
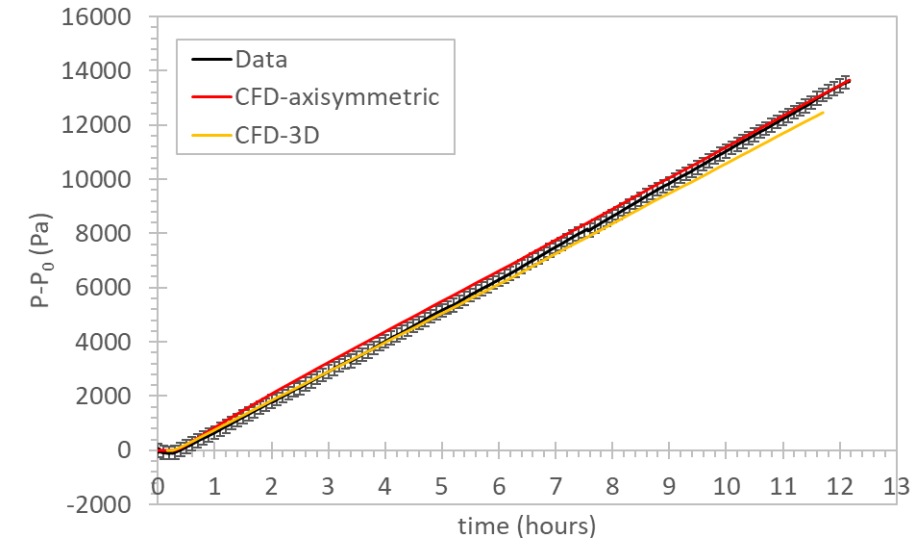
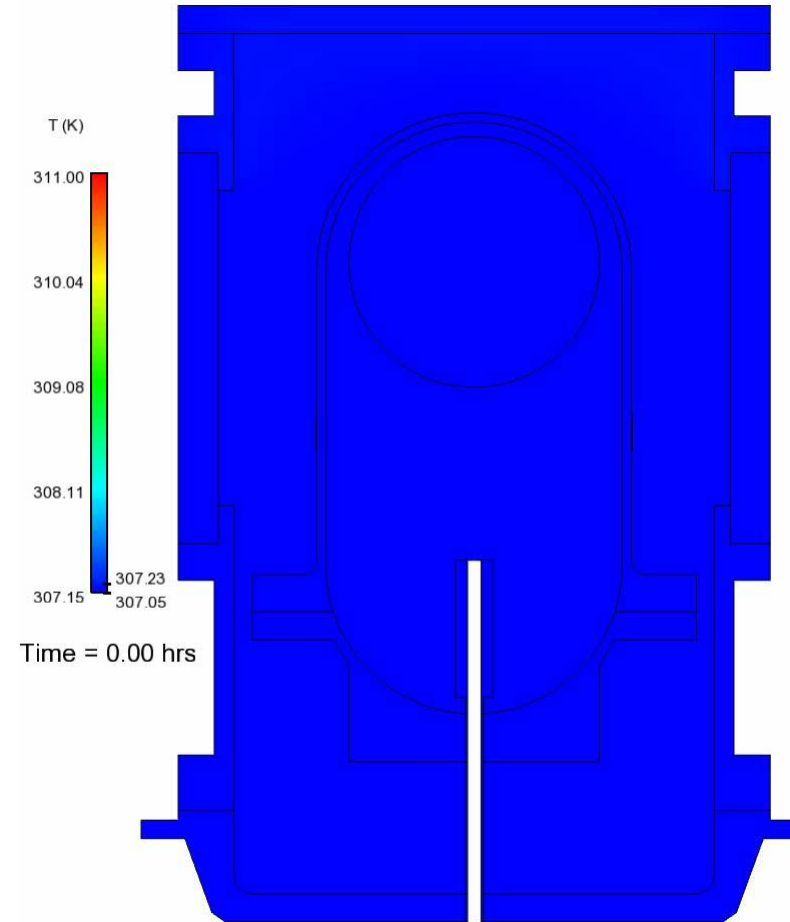


Microgravity Vacuum Jacket Heating Self-Pressurization Test-15: (78%, $T_J = T_w + 1$)



(#15) VJ Self-Press ($T_J = T_w + 1$)
6 hrs 1f/30s

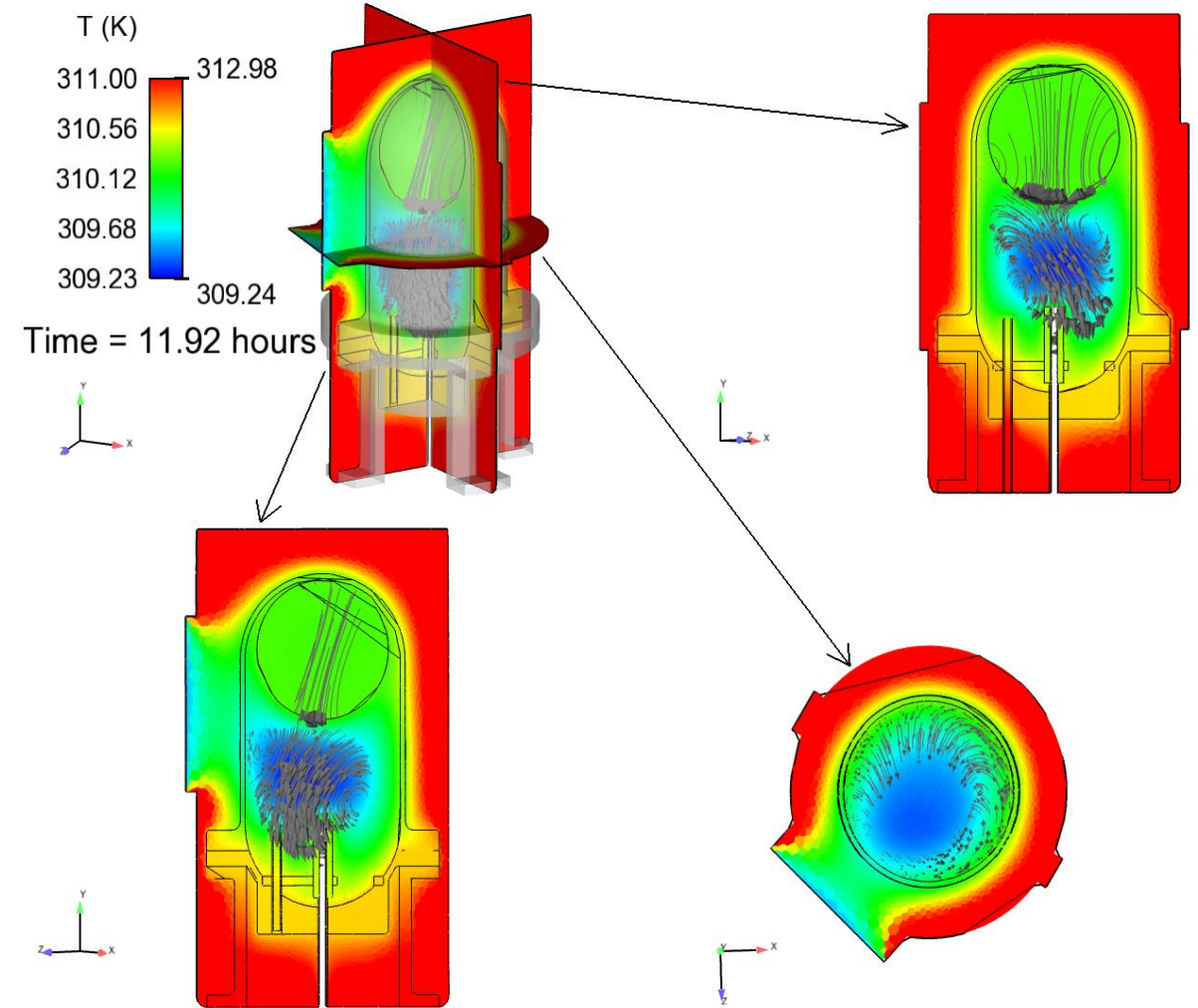
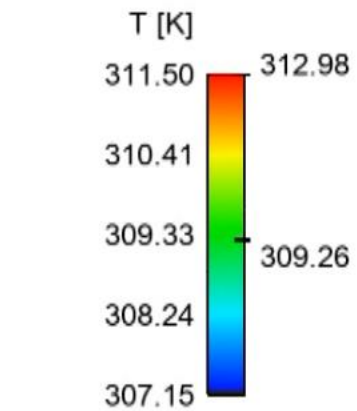
(#15) Axisymmetric CFD Simulation



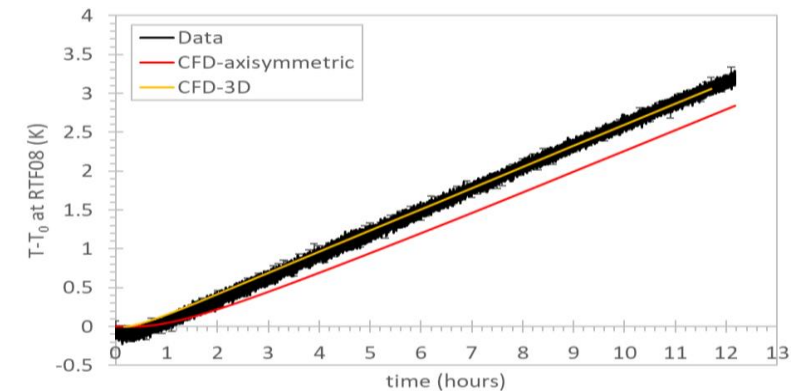
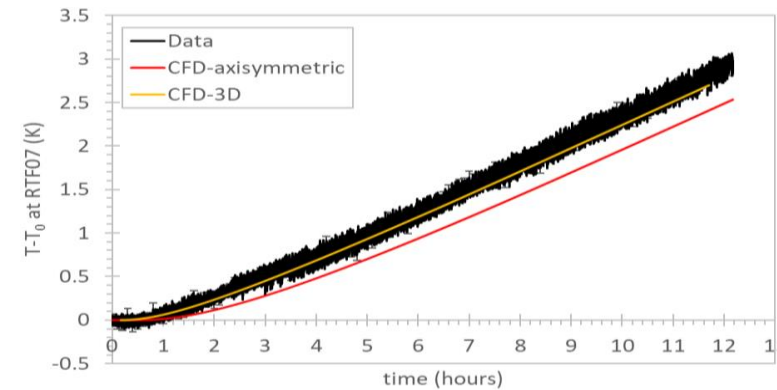
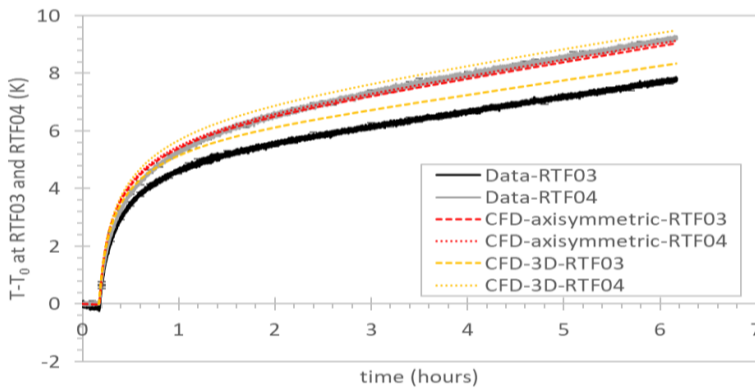
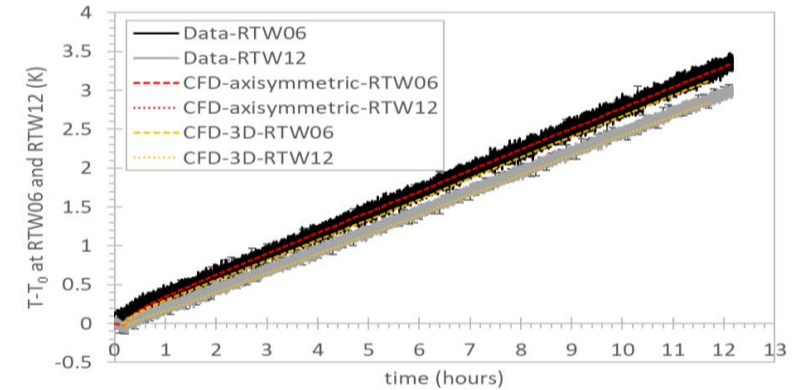
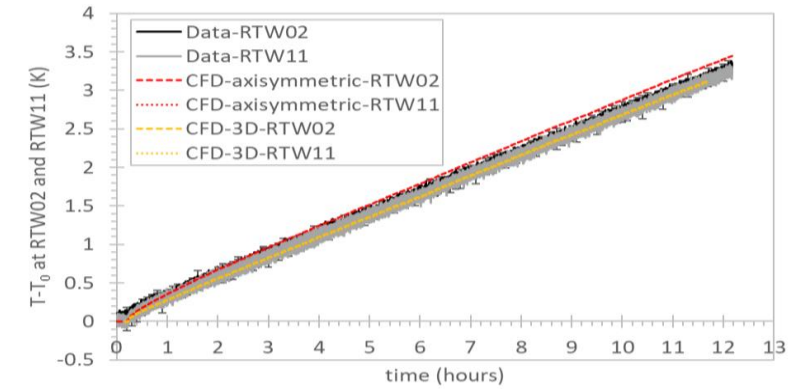
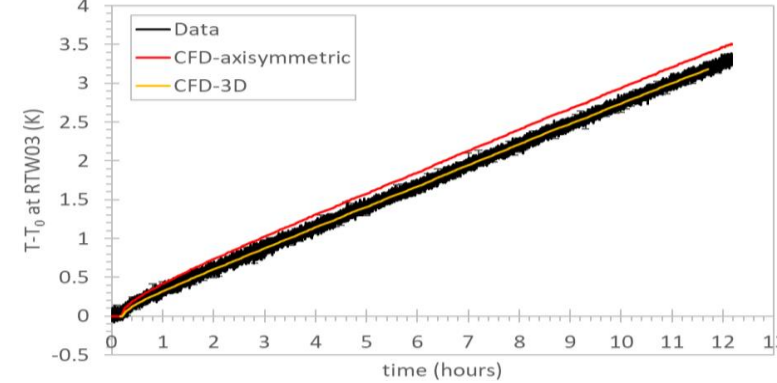
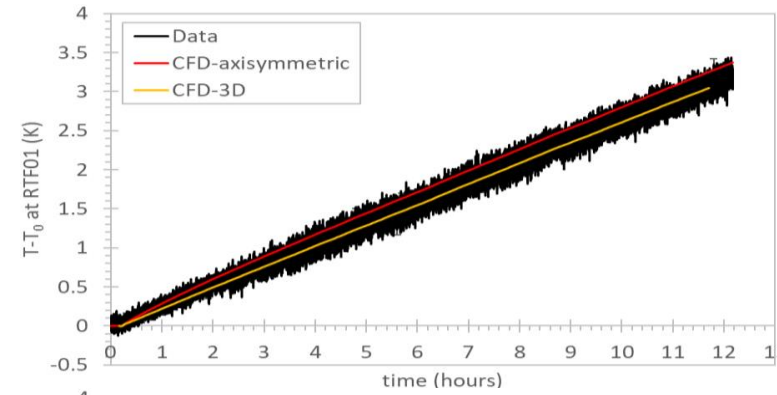
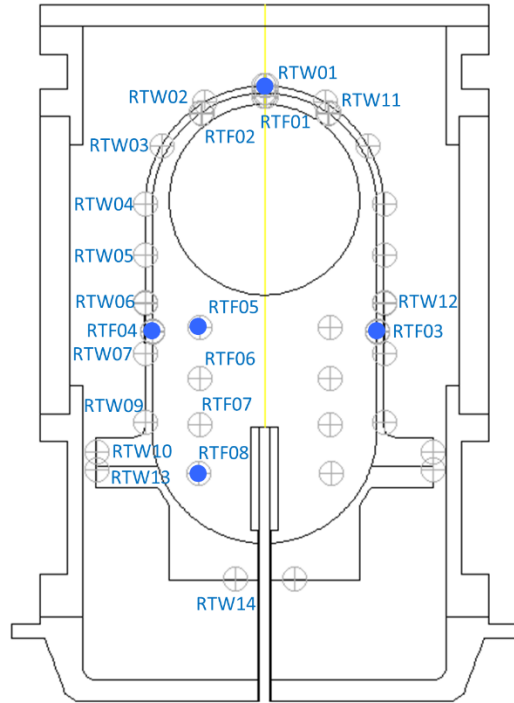
3D Simulation of Microgravity Vacuum Jacket Heating Self-Pressurization Test-15.



Time = 12.00 hours



Microgravity Vacuum Jacket Heating Self-Pressurization Test-15: (78%, $T_J = T_w + 1$)



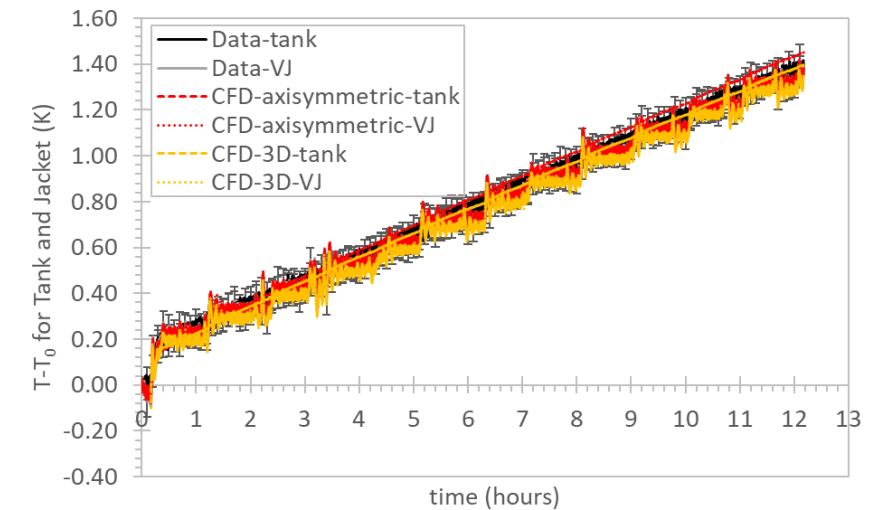
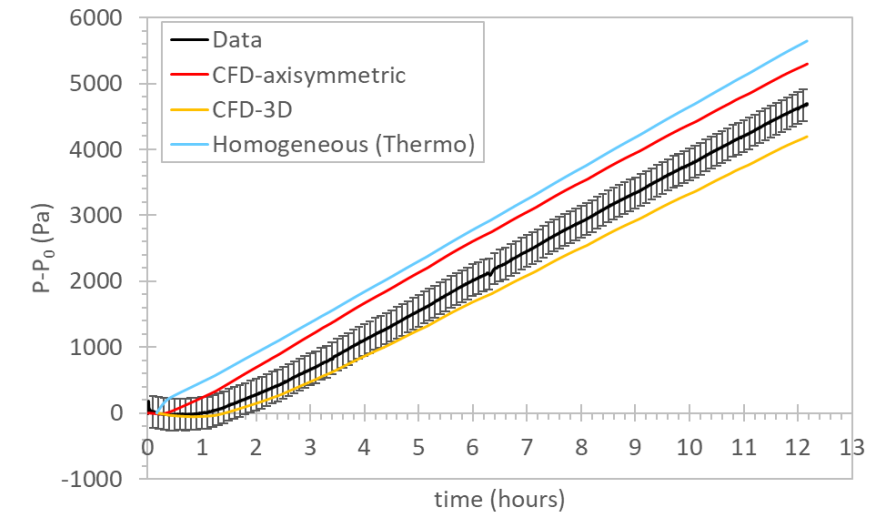
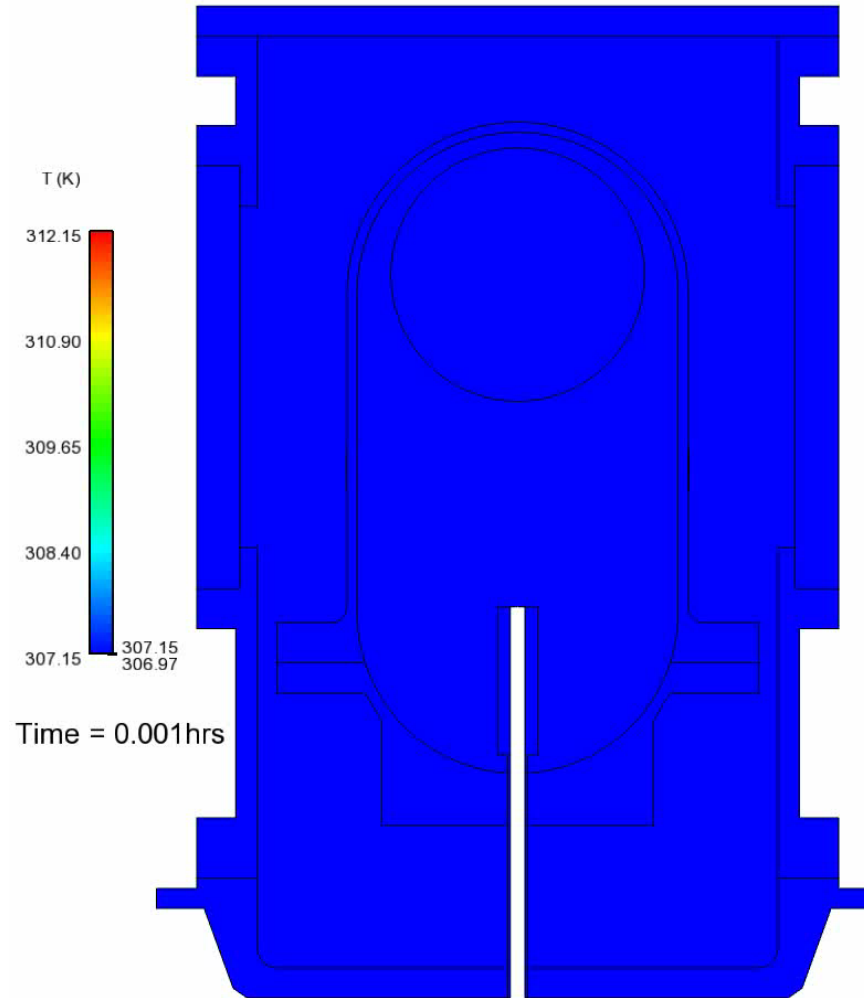
Strip Heater Self-Pressurization Test-230 (0.11W, FL 82%) : Model Validation



6 hrs 1f/30s
(#230) SH Self-Press (0.5W)



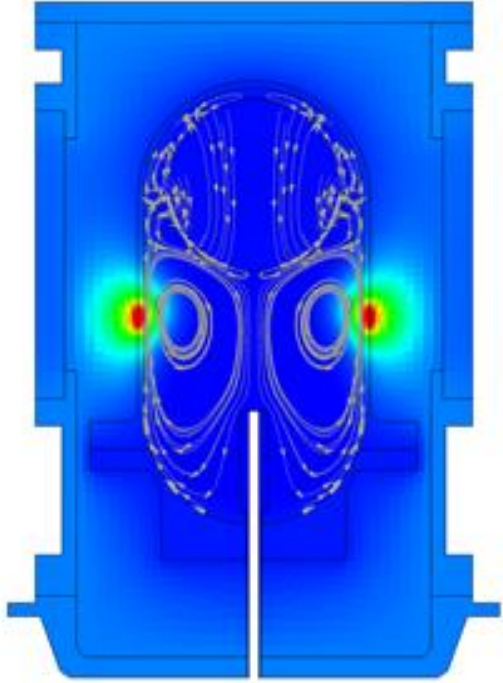
(#215) Axisymmetric CFD Simulation



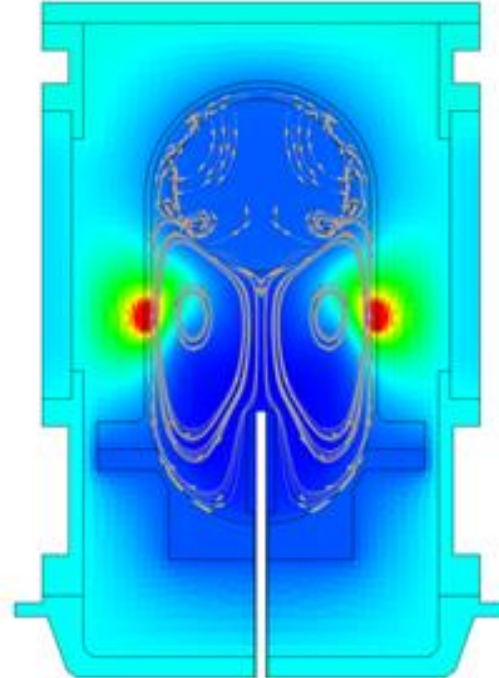
Strip Heater Self-Pressurization (0.5W, FL 70%) : Model Validation



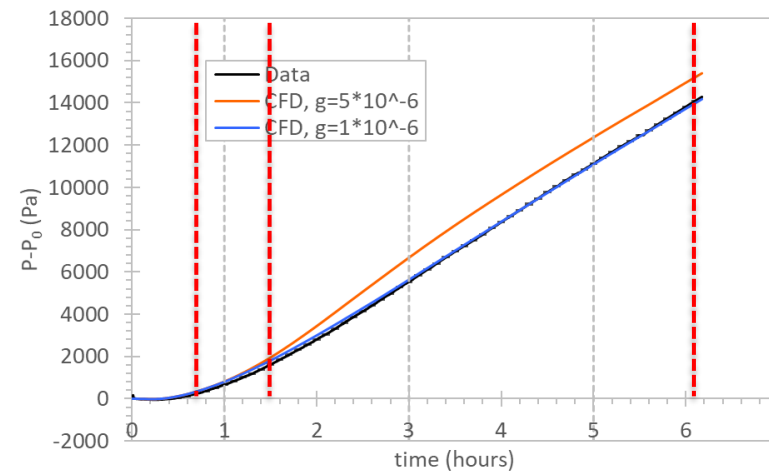
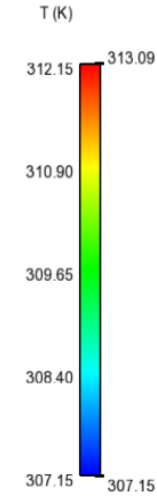
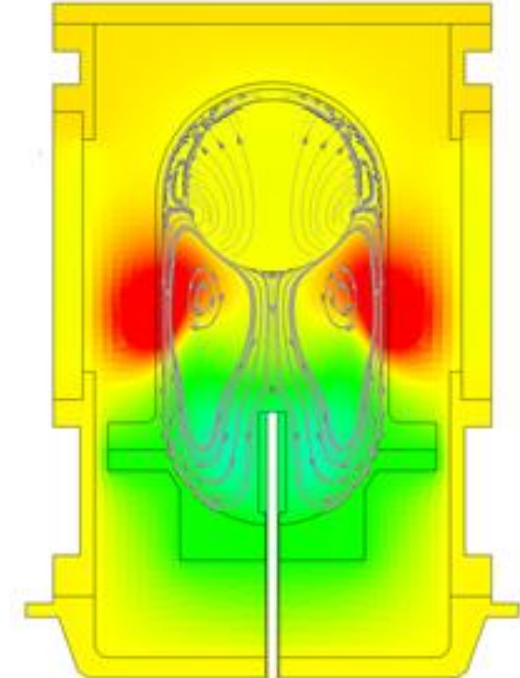
0.75 Hrs.



1.57 Hrs.



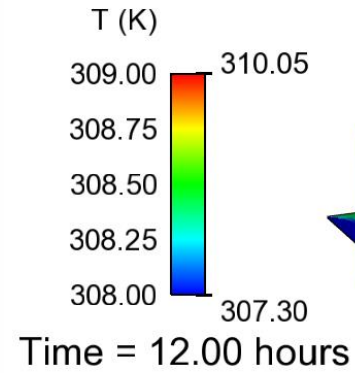
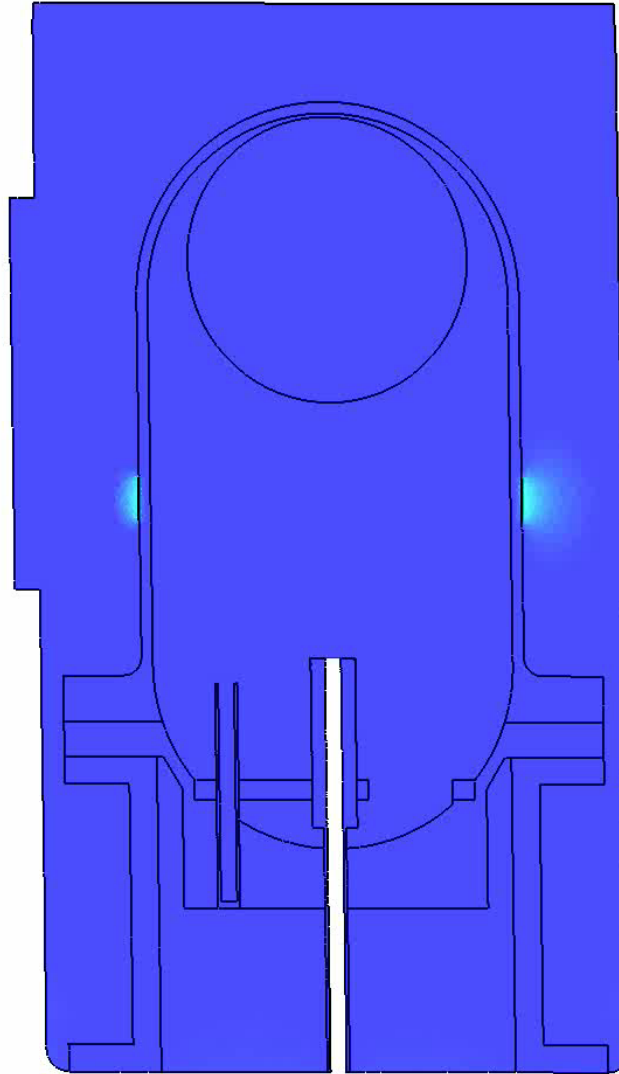
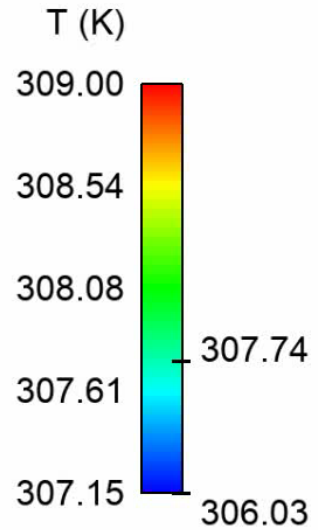
6.17 Hrs.



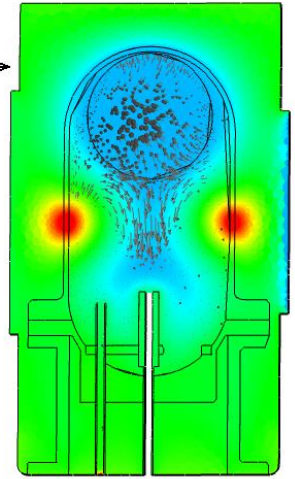
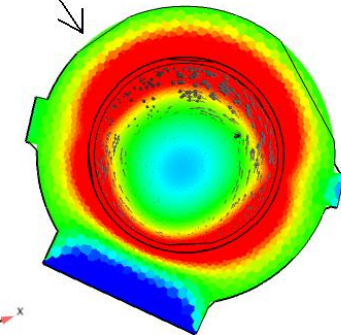
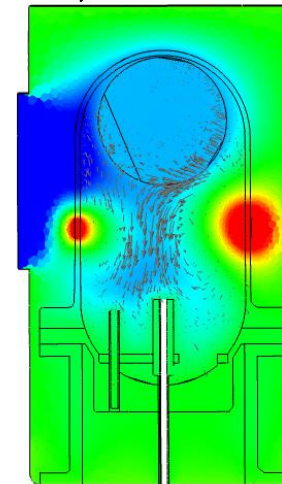
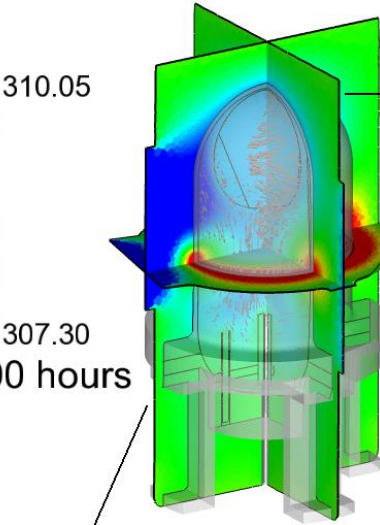
Strip Heater Self-Pressurization Test-230 (0.11W, FL 82%) : Model Validation



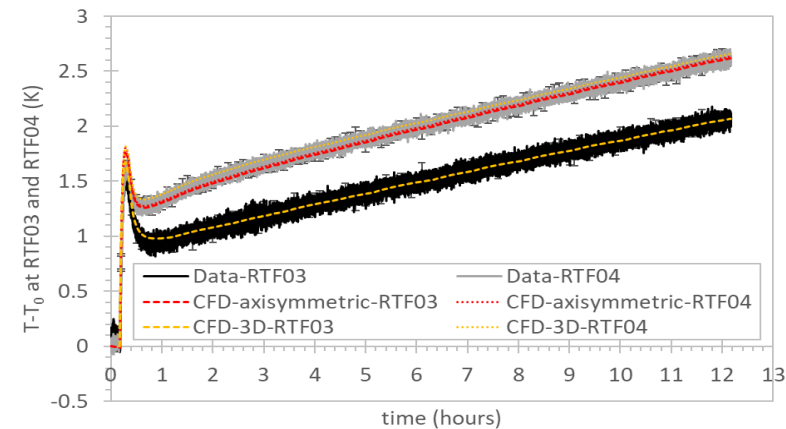
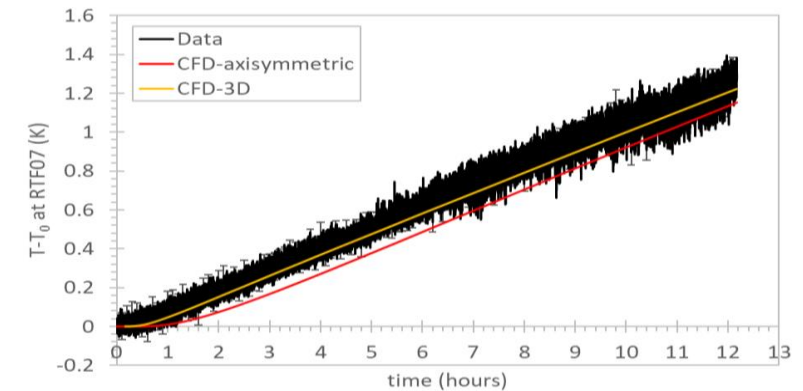
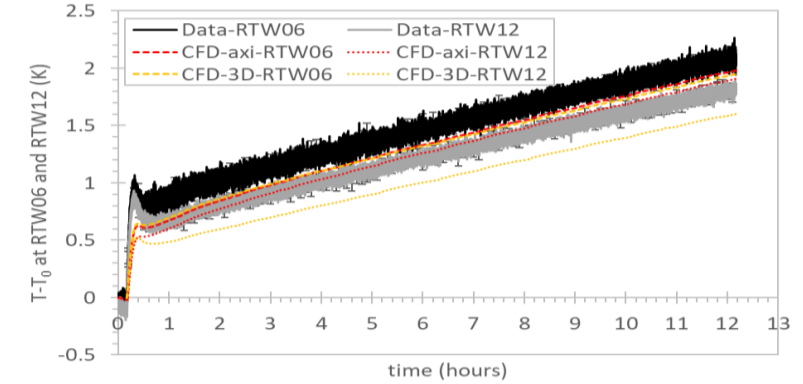
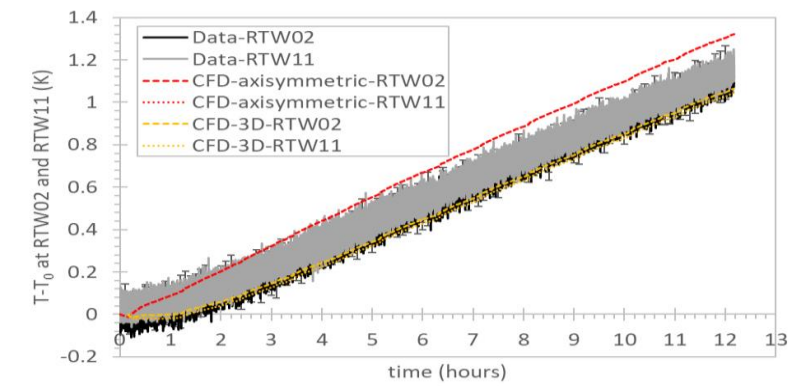
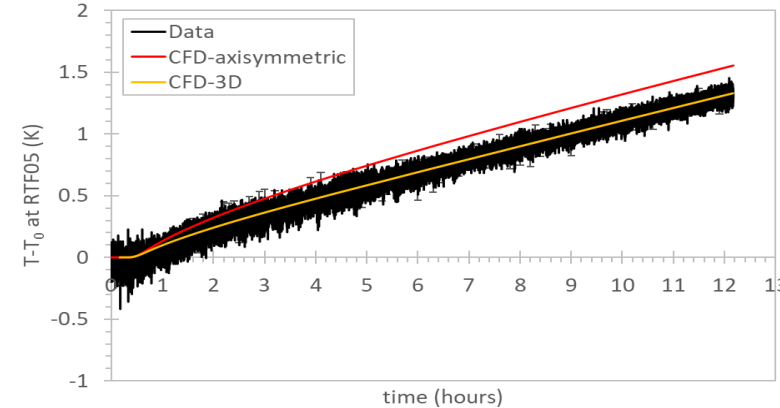
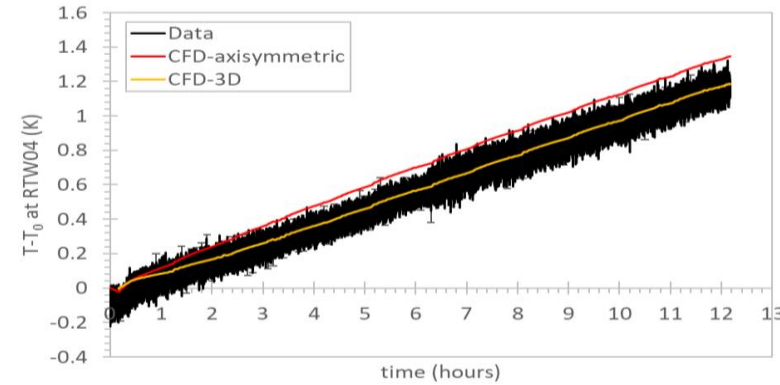
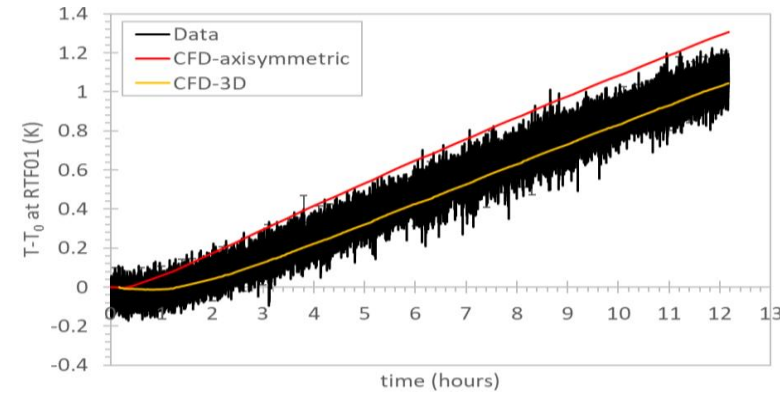
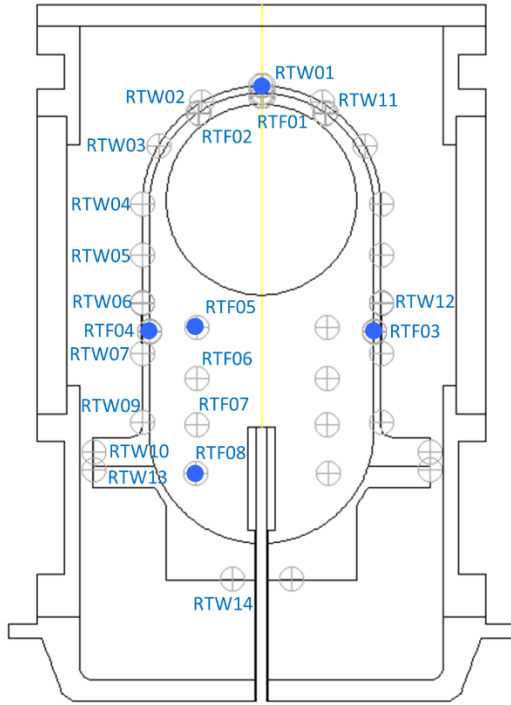
Time = 0.00 hours



Time = 12.00 hours



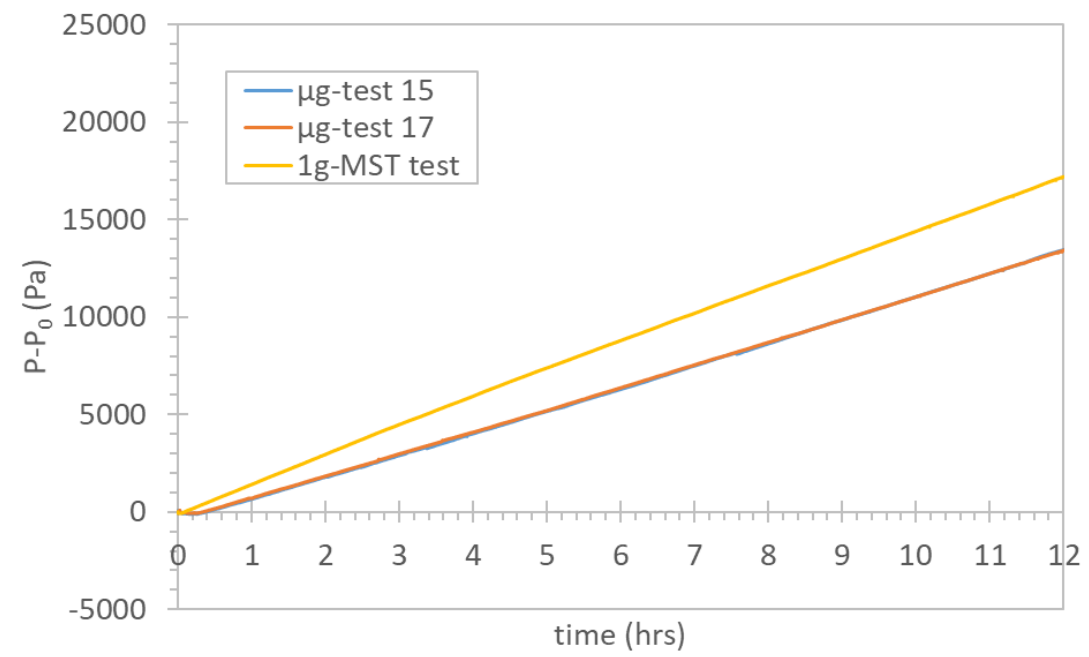
Strip Heater Self-Pressurization Test-230 (0.11W, FL 82%) : Model Validation



Comparison of Microgravity & 1G Self Pressurization Tests

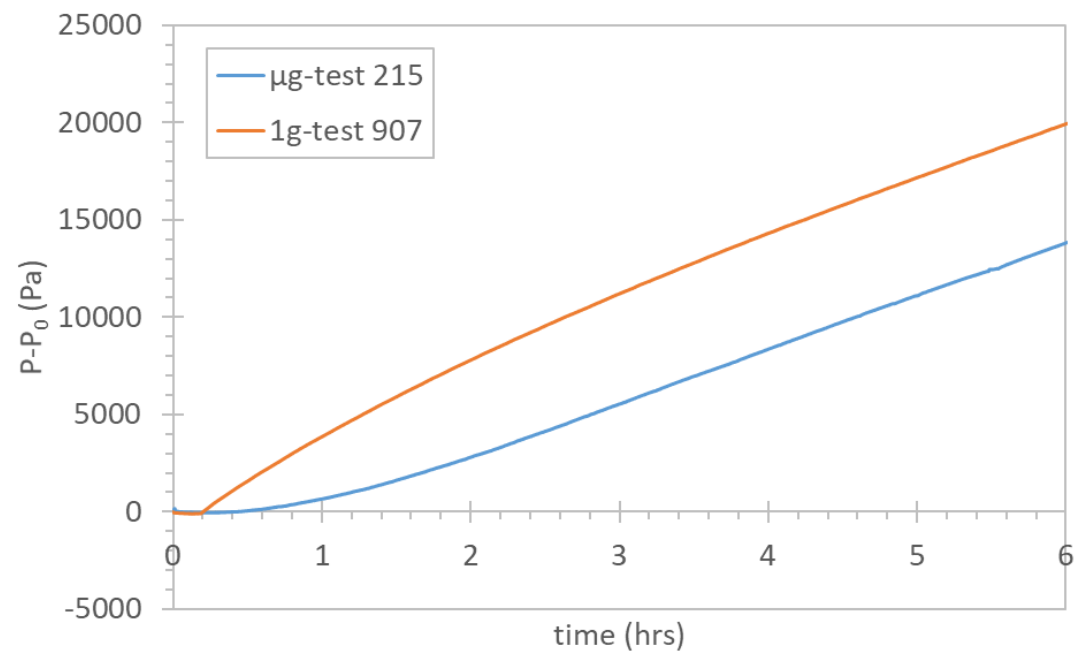


**1G and Microgravity
VJ Self-Pressurization test**



FL = 76%
Q = 0.5 W

**1G and Microgravity
SH Self-Pressurization test**



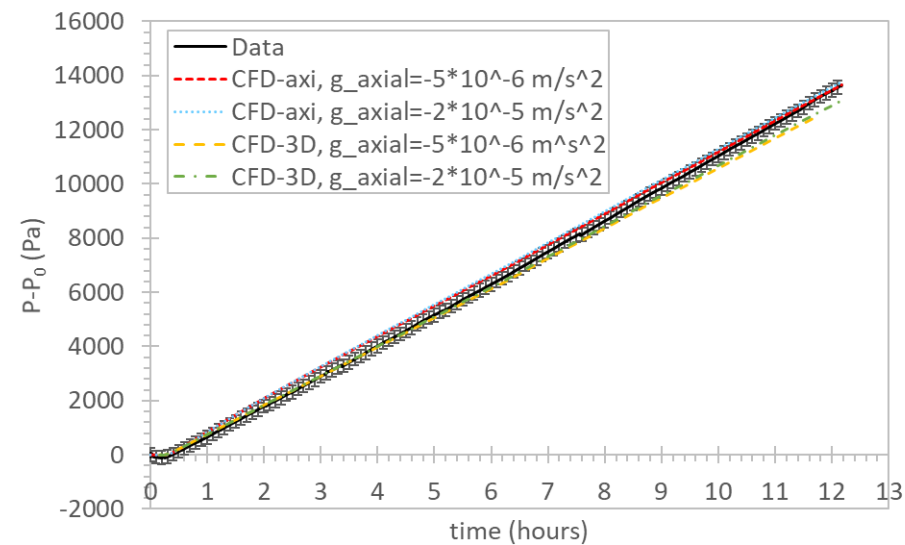
FL = 80%
T_{VJ} = T_w +1 K

Model Validation Comparison of 2D & 3D Model Prediction to Microgravity SH & VJ Self Pressurization Results

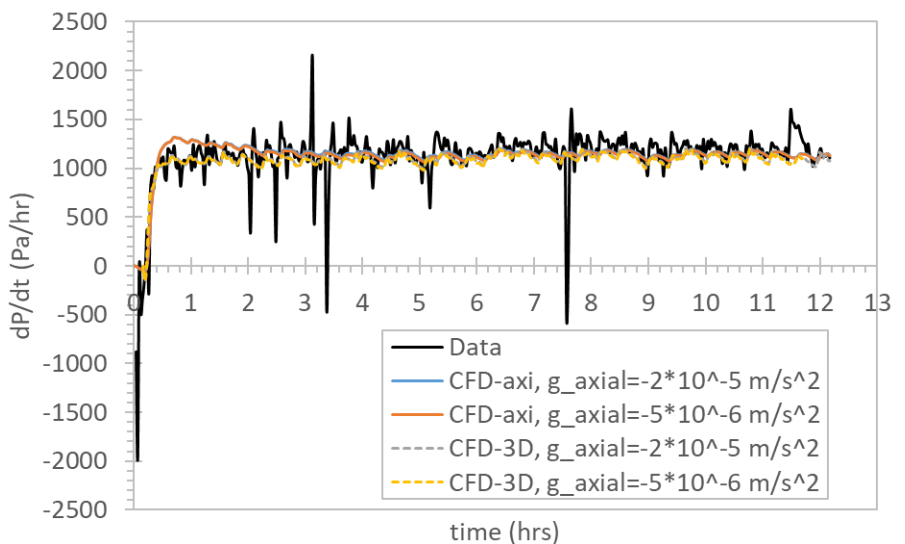


2D & 3D Microgravity VJ Self-Pressurization test-15

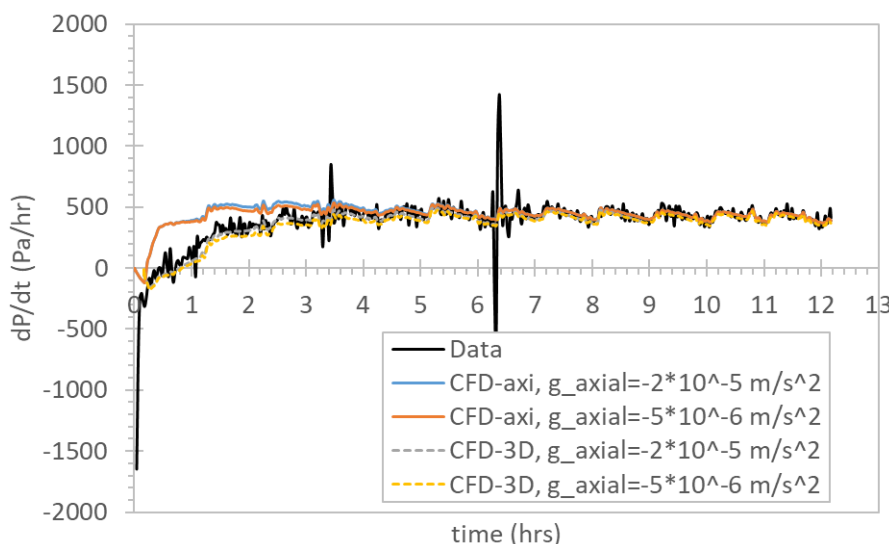
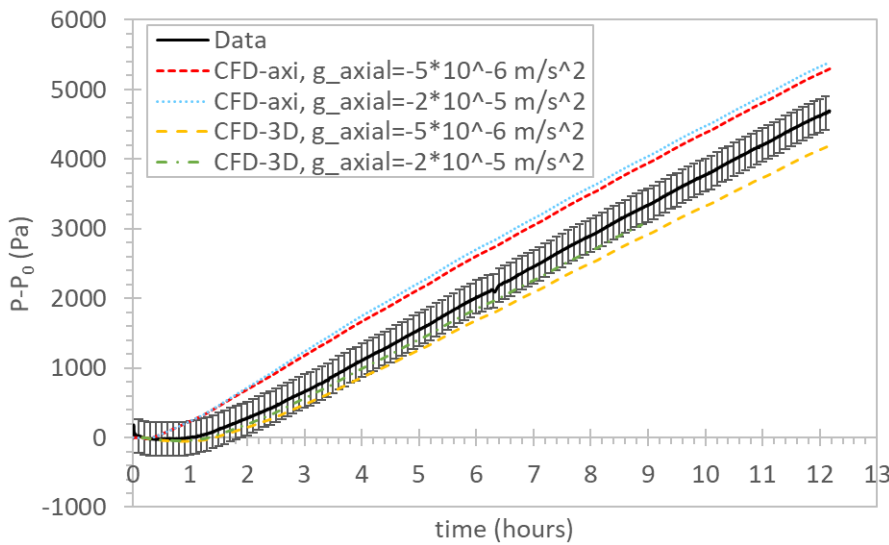
2D & 3D Microgravity SH Self-Pressurization test-230



FL = 70%
 $T_{VJ} = T_T + 1$



FL = 76%
Q = 0.5 W
FL = 80%
 $T_{VJ} = T_w + 1 \text{ K}$

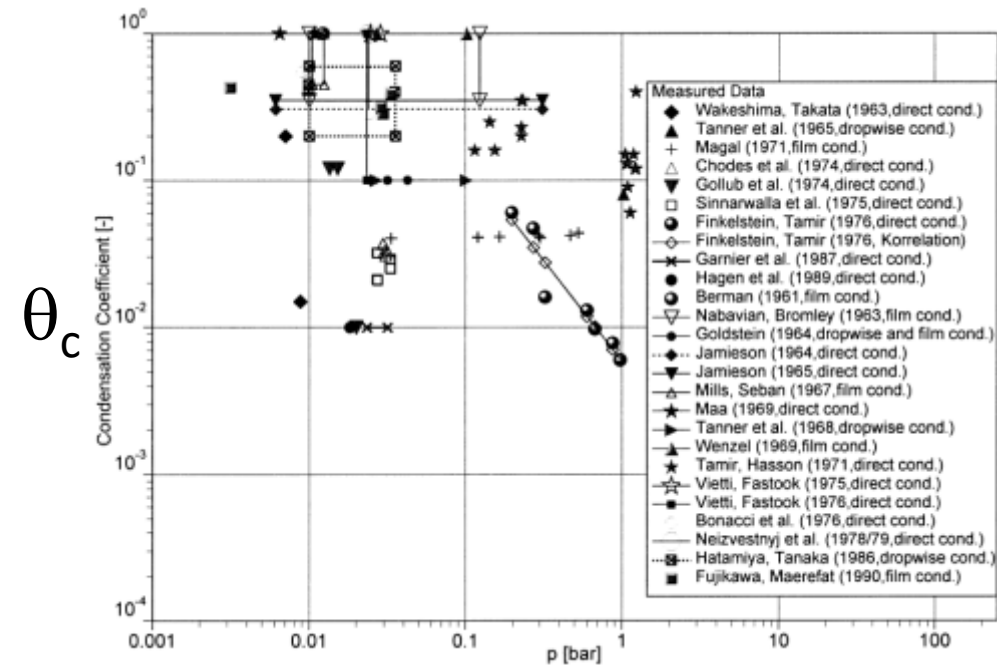
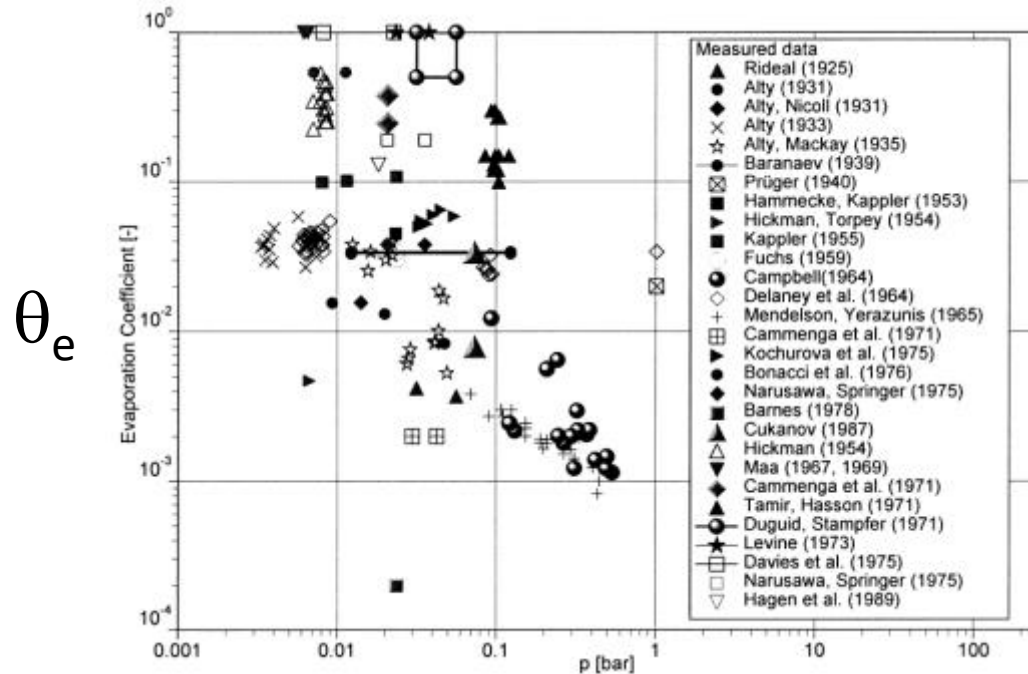


Phase Change Accommodation Coefficient(s)



$$\dot{m} = \left(\frac{2}{2 - \theta_c} \right) \left(\frac{1}{\sqrt{2\pi R}} \right) \left[\frac{\theta_e P_l}{\sqrt{T_l}} - \frac{\theta_c P_v}{\sqrt{T_v}} \right]$$

- Fraction of vapor molecules that reflect off the surface (evaporation/condensation)
- 80+ years of measurements yields *3+ orders of magnitude difference*
- Variations due to wall material, geometry, contact angle



Evaporation/Condensation coefficients for water

Marek and Straub, *Int. J. Heat Mass Trans.* 44.1 (2001): 39-53.

Self-Pressurization Simulations using Schrage Kinetics Phase Change Mass Transfer Model



Interfacial Energy Balance:

$$T_I = T_{sat}(P_v)$$

$$LJ_v = -k_l \vec{\nabla} T_l \cdot \hat{n} + k \cdot \vec{\nabla} T \cdot \hat{n}$$

Schrage Interfacial Mass Transfer:

$$J_v = \frac{2\sigma}{2-\sigma} \frac{1}{\sqrt{2\pi R T_I}} [P_{sat}(T_I) - P_v]$$

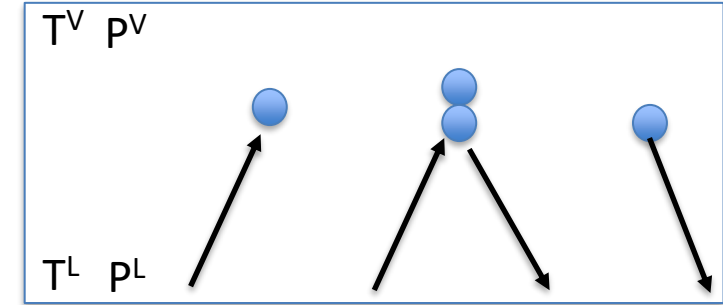
$$\frac{P_{sat}(T_I)}{P_r} = e^{\left[\frac{L}{R} \left(\frac{1}{T_r} - \frac{1}{T_I} \right) \right]}$$

From Gas Kinetics

Maxwellian Velocity Function

$$\phi_V = \frac{P^V}{\sqrt{2\pi R T^V}}$$

$$\phi_L = \frac{P^L}{\sqrt{2\pi R T^L}}$$



$$\dot{m} = f_e \phi_L - f_c \phi_V$$

$$f_e = f_c = \frac{2\sigma}{2-\sigma}$$

$$\dot{m} = \frac{2\sigma}{2-\sigma} \frac{1}{\sqrt{2\pi R}} \left(\frac{P^L}{\sqrt{T^L}} - \frac{P^V}{\sqrt{T^V}} \right)$$

Schrage Equation

For near-Equilibrium conditions

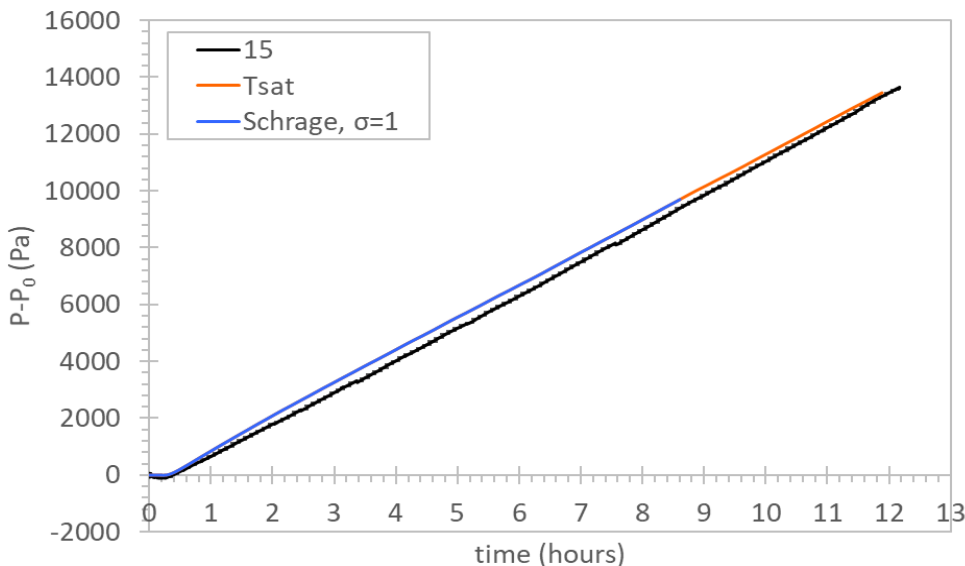
$$T^V = T^L = T_I$$

$$P^L = P_{sat}(T_I)$$

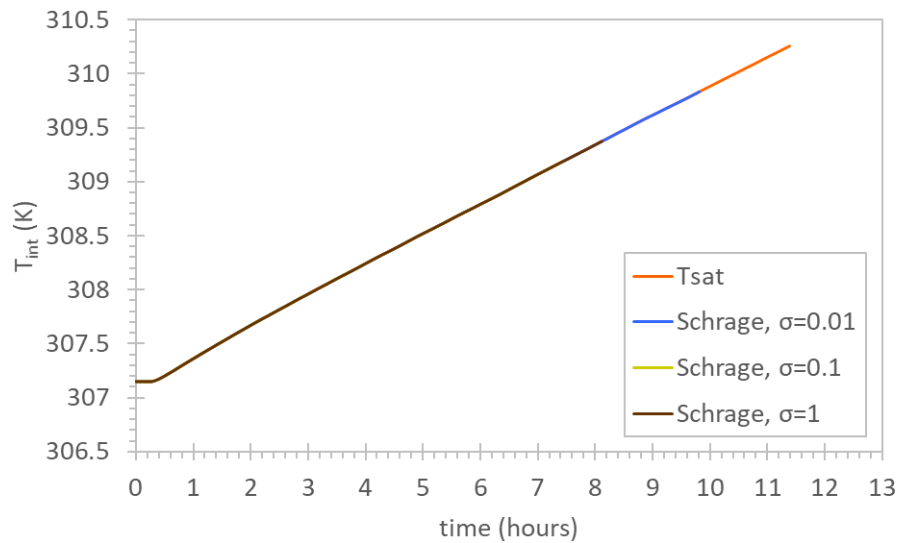
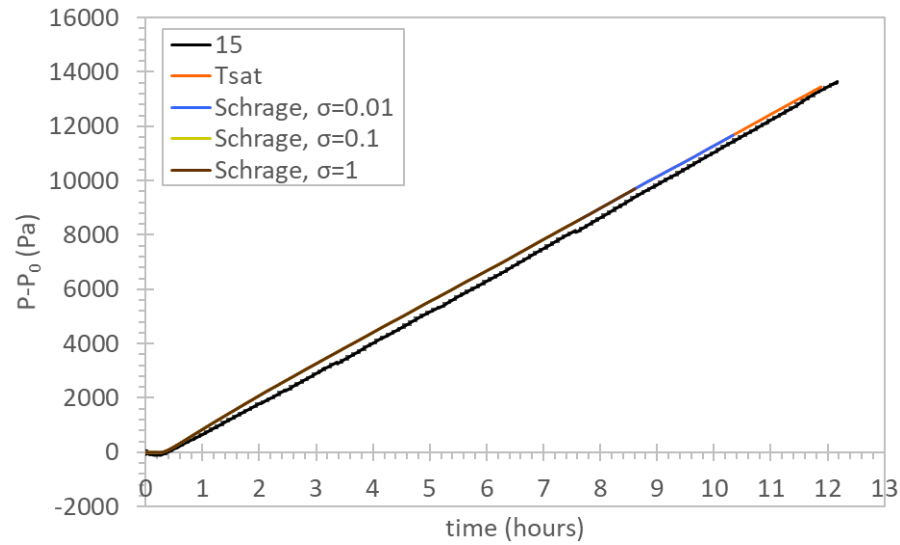
$$\dot{m} = \frac{2\sigma}{2-\sigma} \frac{1}{\sqrt{2\pi R T_I}} (P_{sat}(T_I) - P_V)$$

Using linearized Clausius Clapeyron

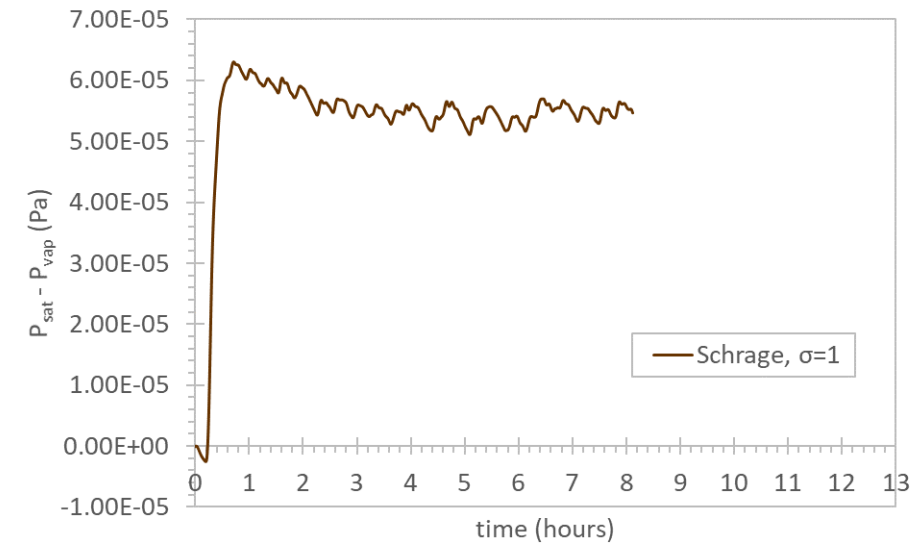
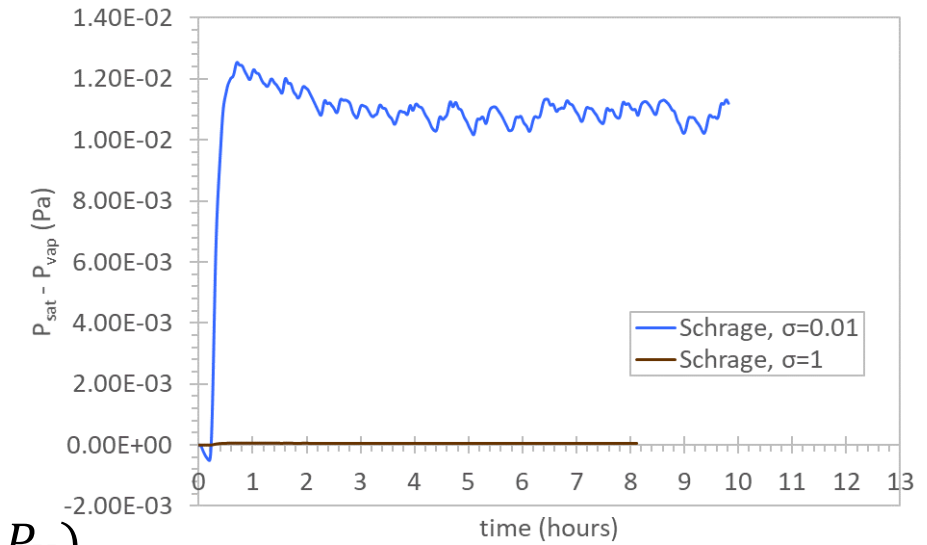
$$\dot{m} = \frac{q''}{L} = \frac{T_I - T_{sat}}{R_{int} L} \quad R_{int} = \frac{2-\sigma}{2\sigma} \frac{\sqrt{2\pi R}}{L^2} \left(\frac{T_{sat}^{3/2}}{\rho_V} \right)$$



Self-Pressurization Simulations using Schrage – Effect of Accommodation Coefficient



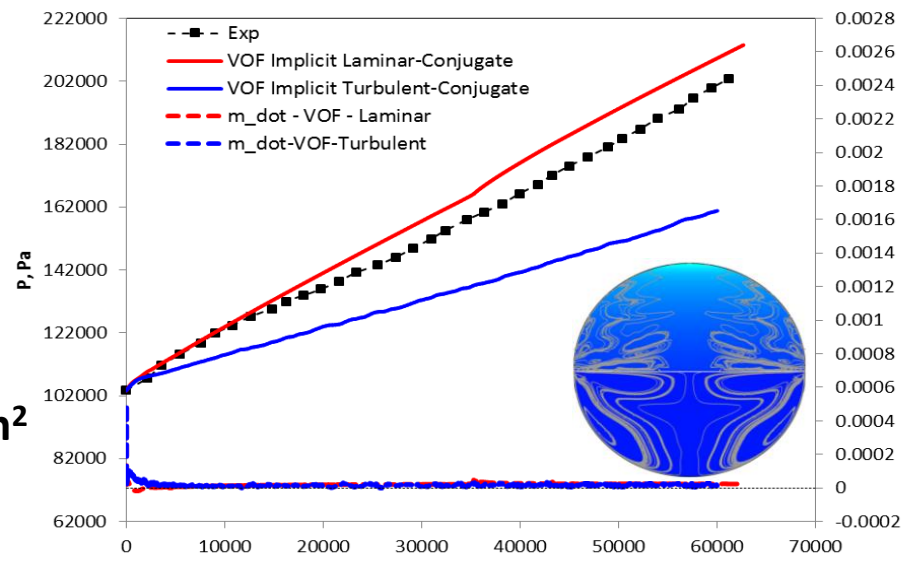
$$\dot{m} = \frac{\sigma}{2-\sigma} \frac{1}{\sqrt{2\pi RT_I}} (P_{sat}(T_I) - P_V)$$



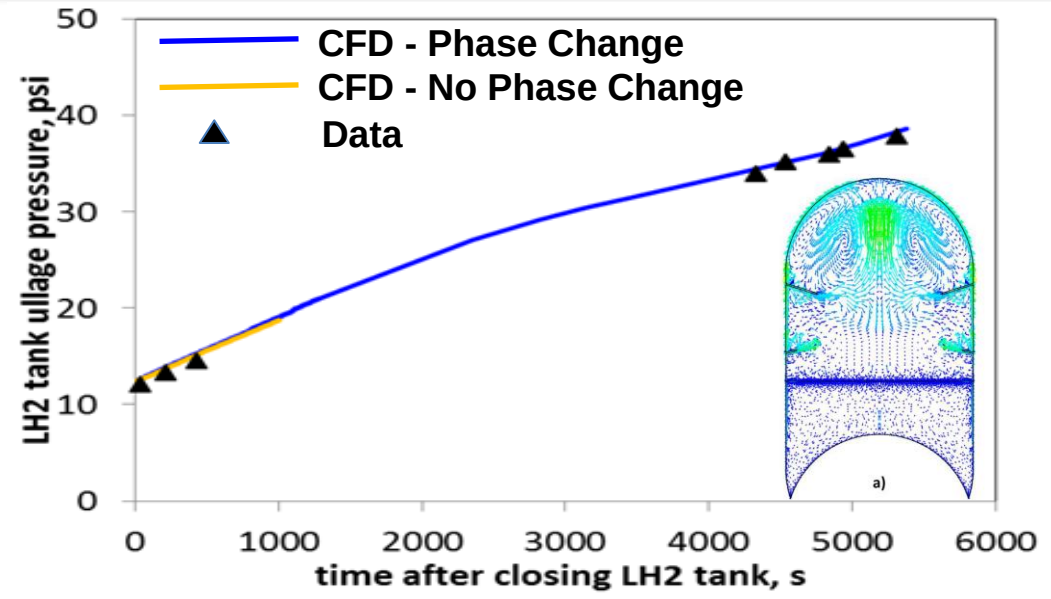
The Tale of The Four Tanks



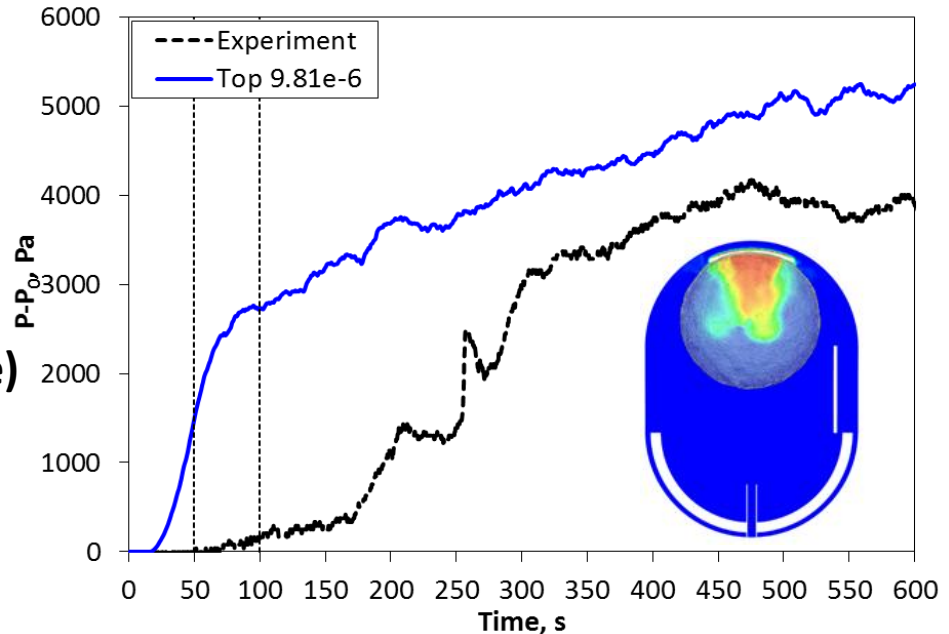
K-Site
1G
LH2
Large
(GRC)
3.5 W/m²



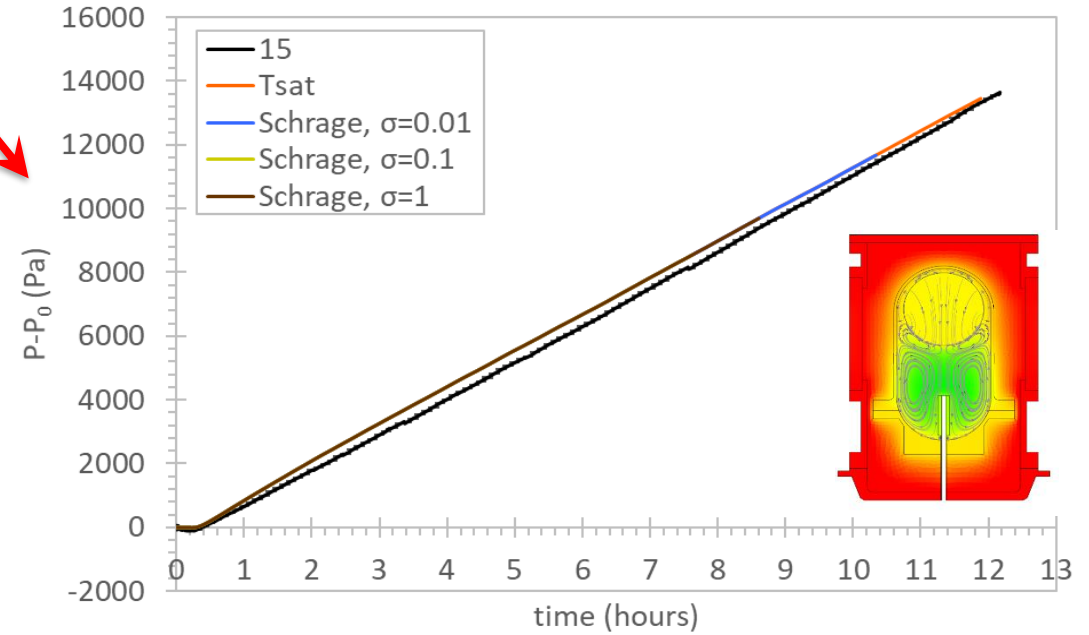
Saturn IVB
0G
LH2
V. Large
(Saturn
AS203)
~30,000 W
~150 W/m²



TCPE
0G
Freon
Small
(Shuttle)
16 W
900
W/m²



ZBOT
0g
PnP
Small
(ISS)
3-8
W/m²





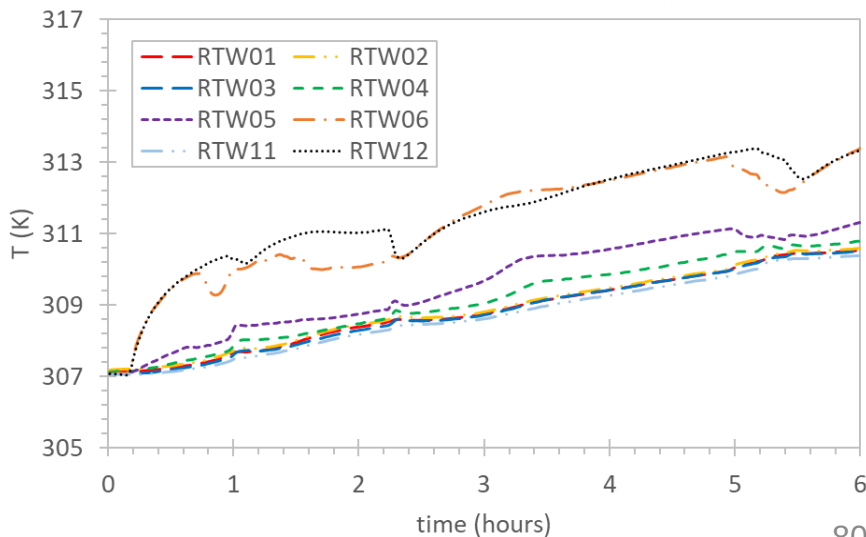
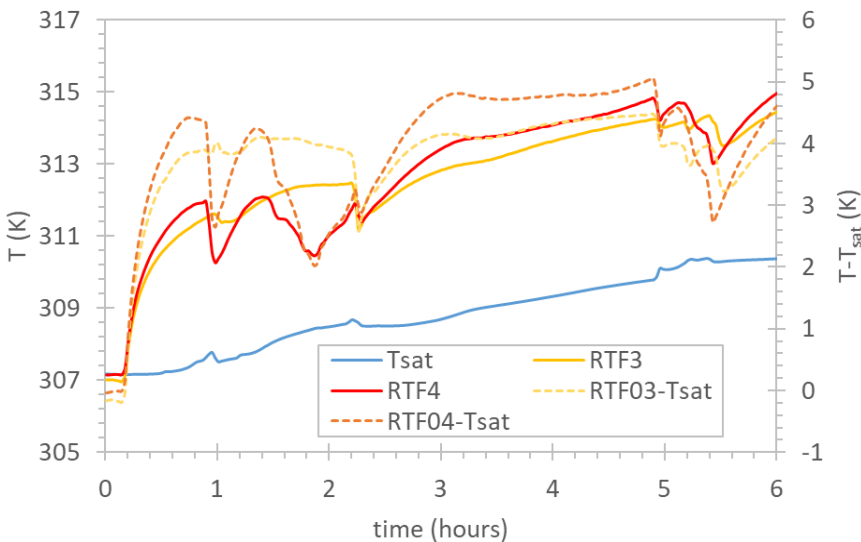
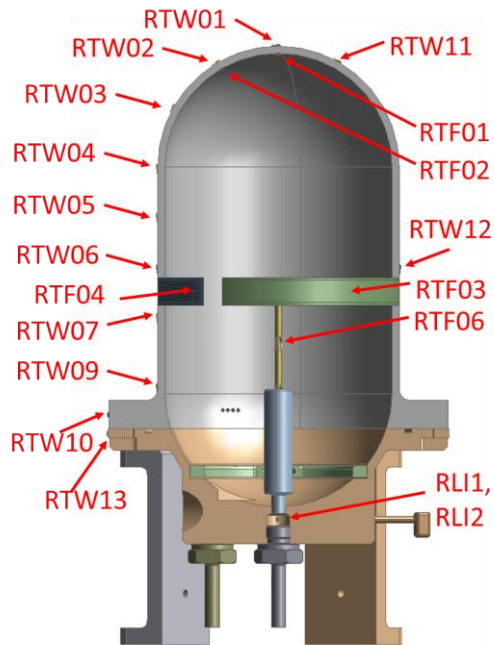
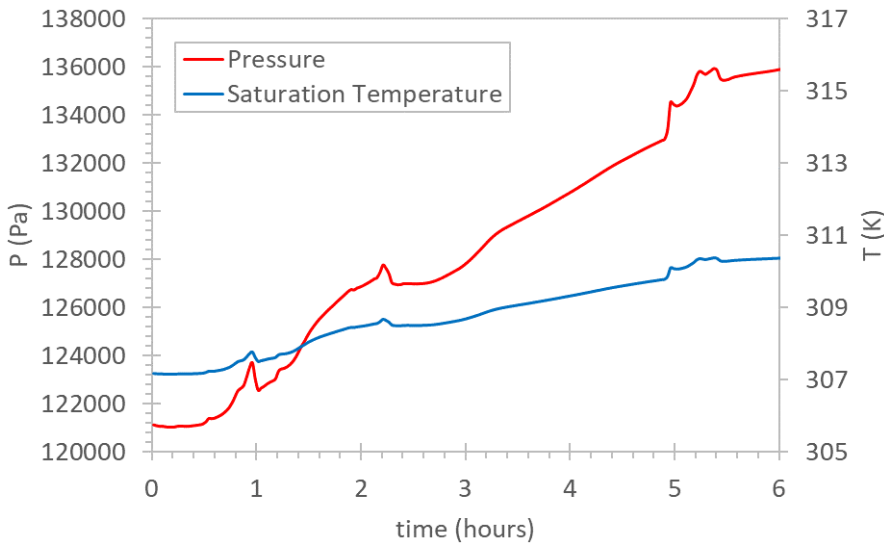
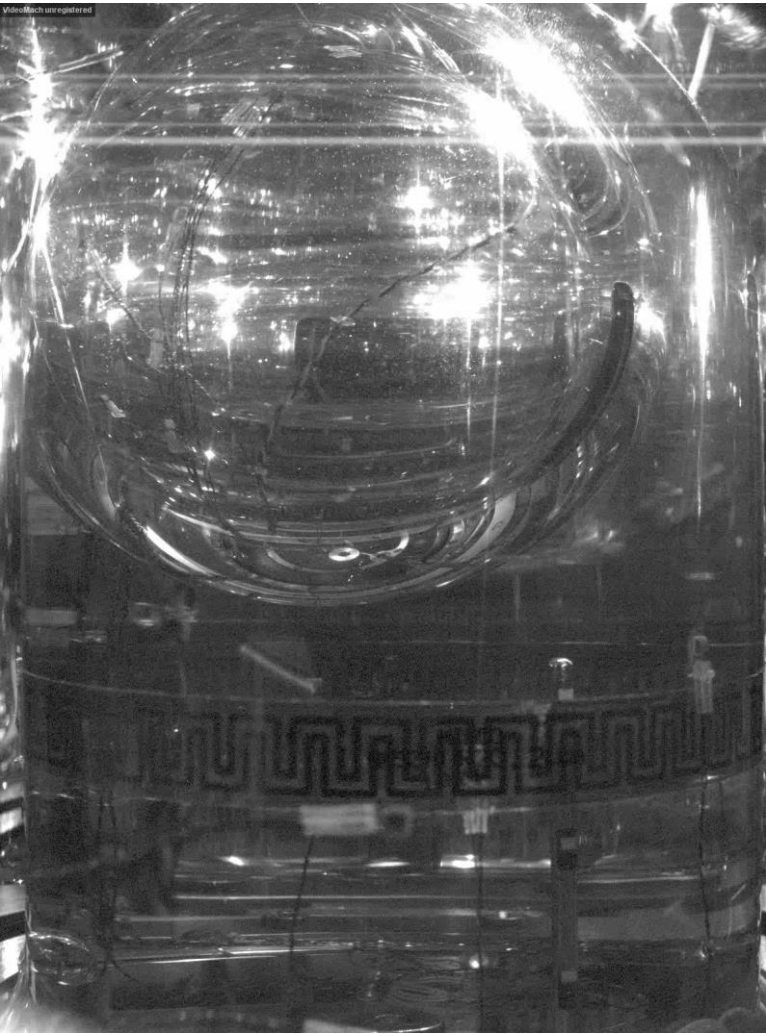
Boiling during Microgravity Self-Pressurization

Microgravity Strip Heating (0.5 W) Self-Pressurization

– Localized Microgravity Boiling



(#208) SH Self-Press (78%)
6 hrs 1f/30s



Microgravity Strip Heating Self-Pressurization

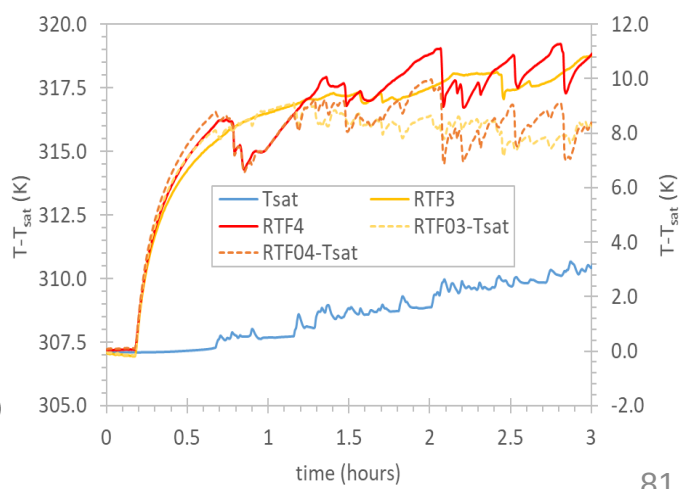
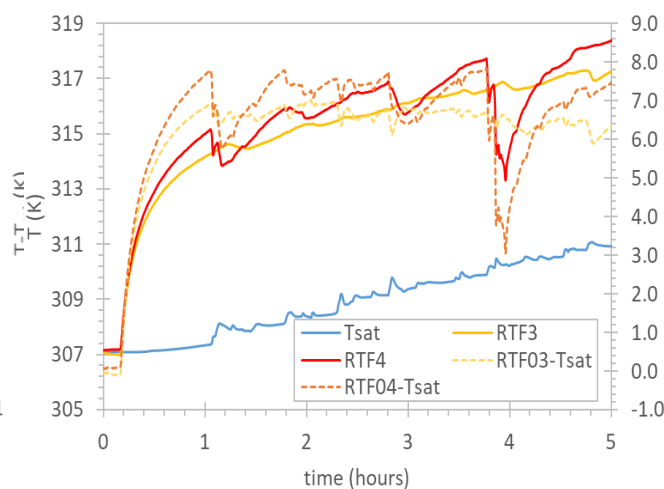
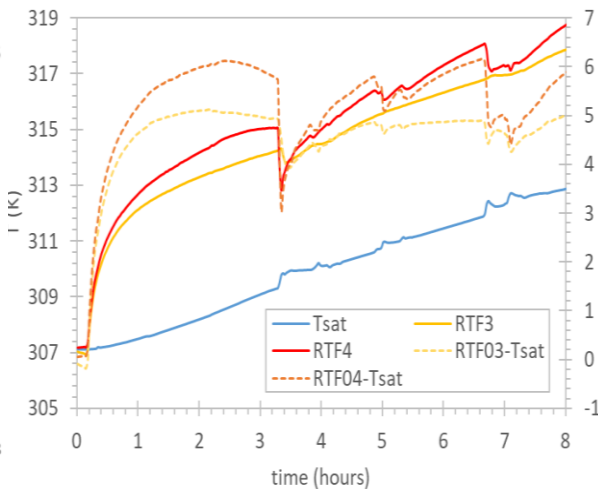
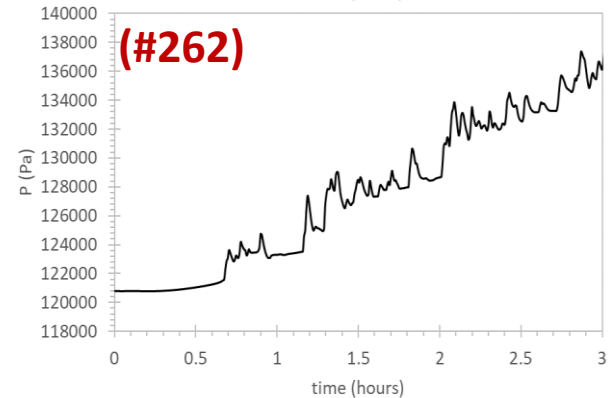
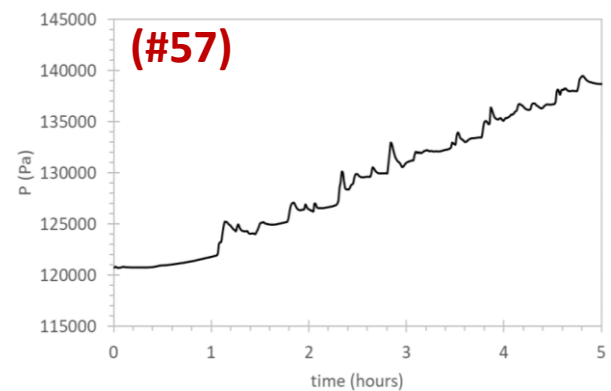
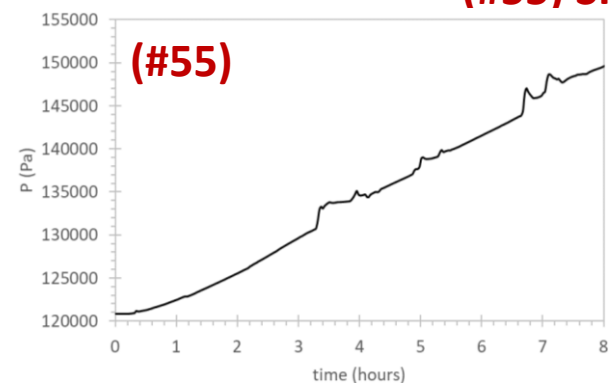


– Sustained Microgravity Boiling at higher Heat Fluxes

(#55) SH+VJ Self-Press (0.5W + $T_J = T_w + 1$)

(#57) SH Self-Press (0.75 W)

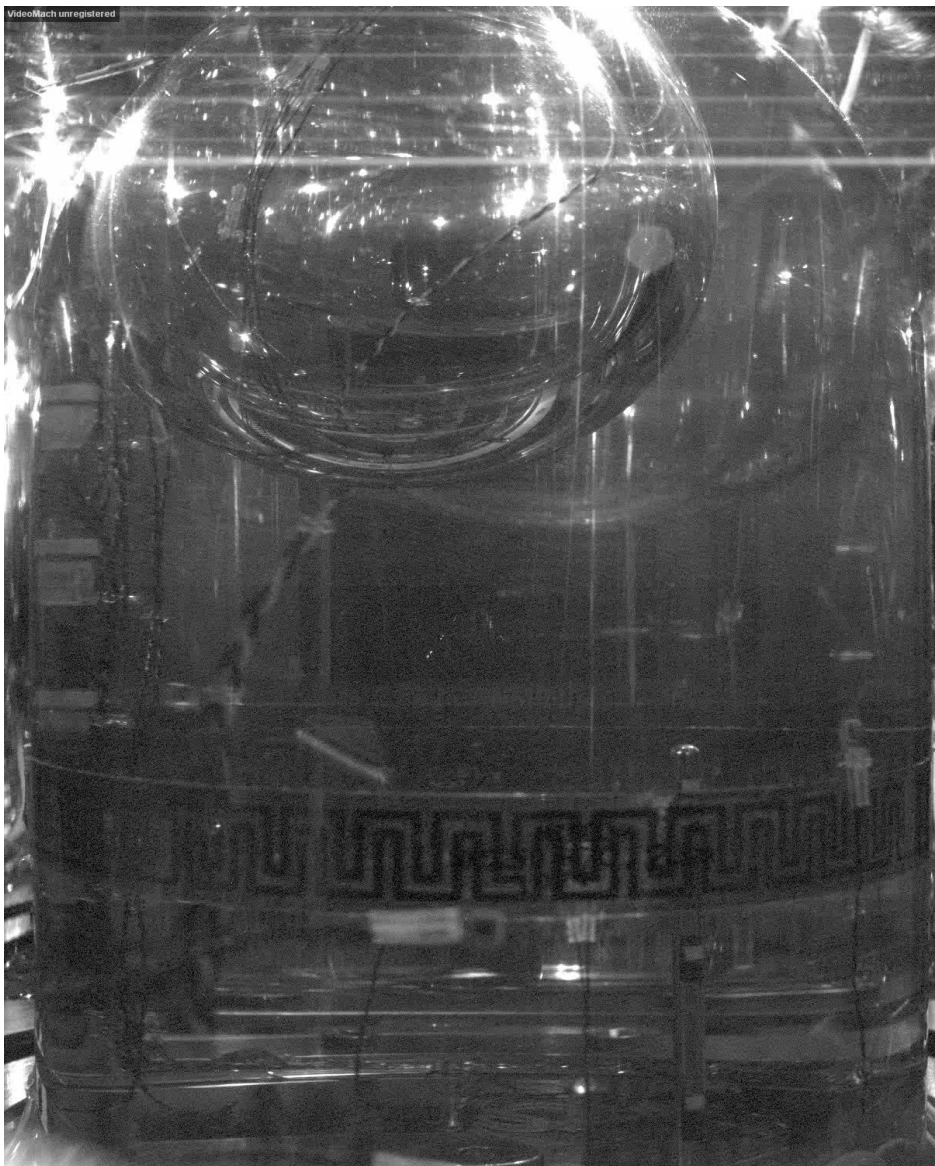
(#262) SH Self-Press (1.0 W)



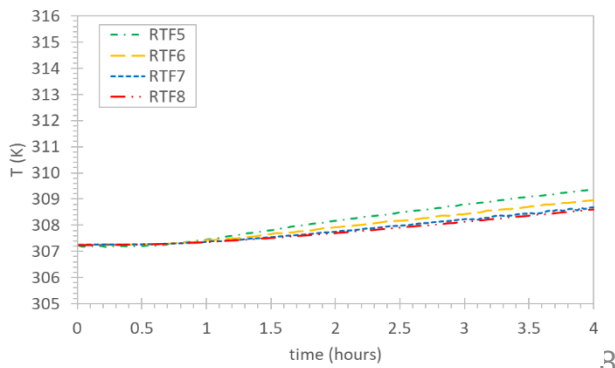
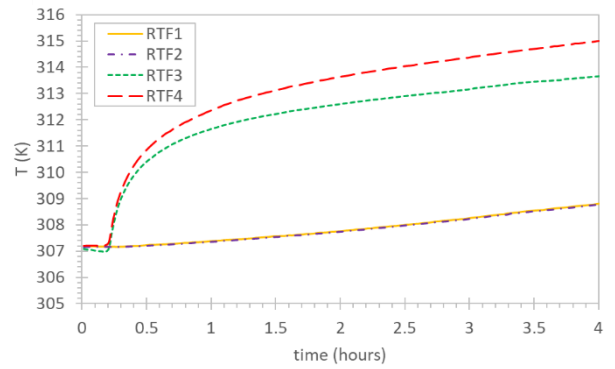
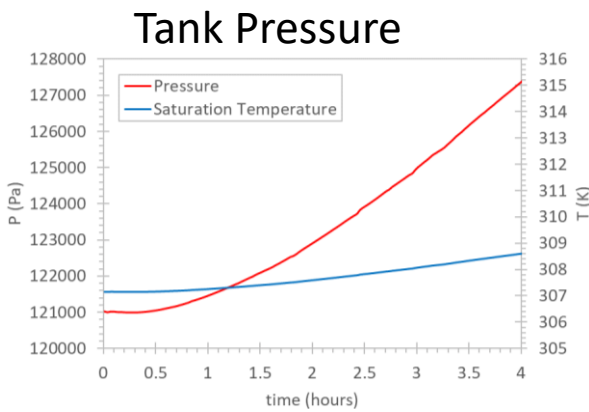
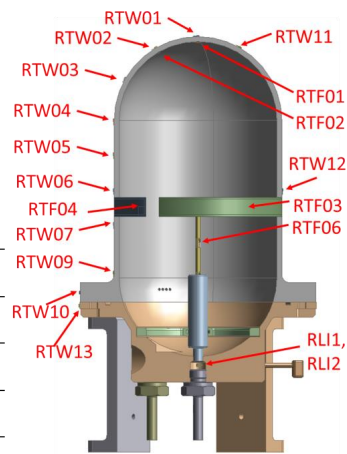
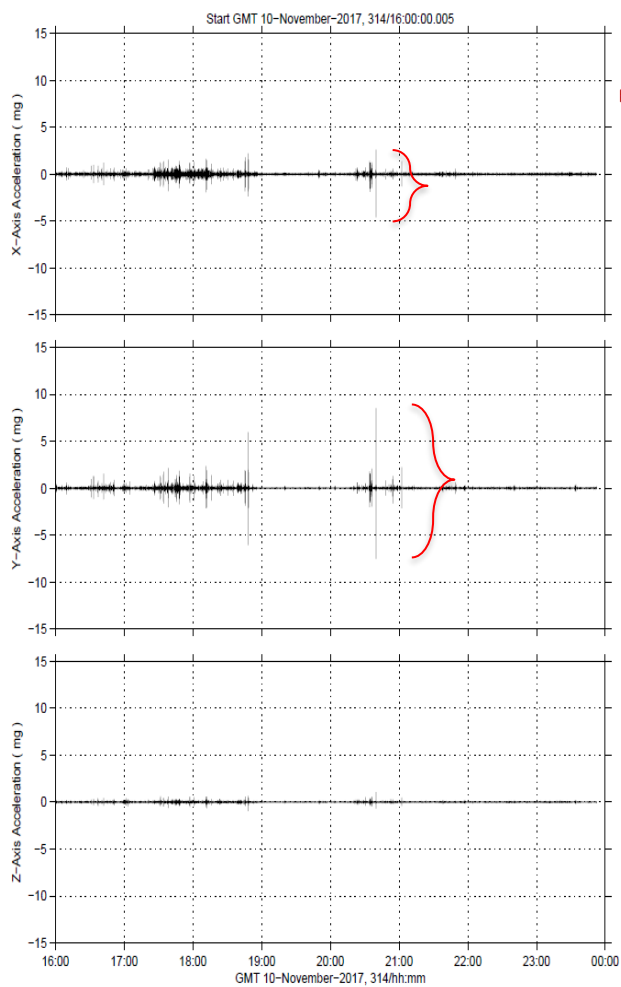


Impact of Sudden Acceleration on Microgravity Self-Pressurization

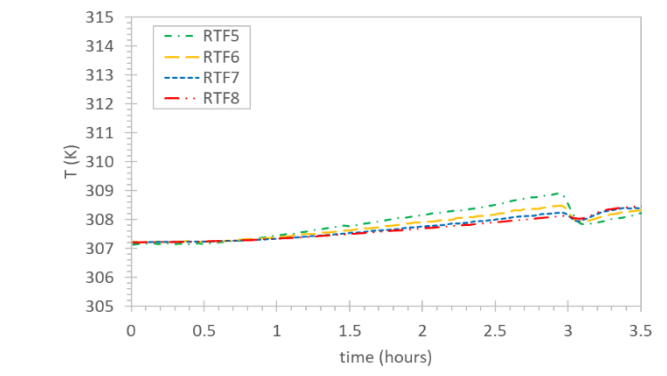
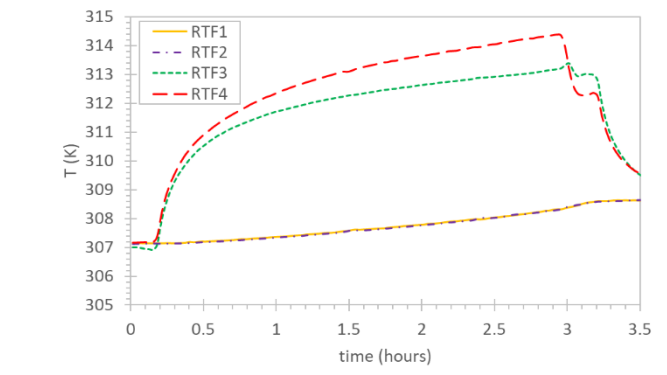
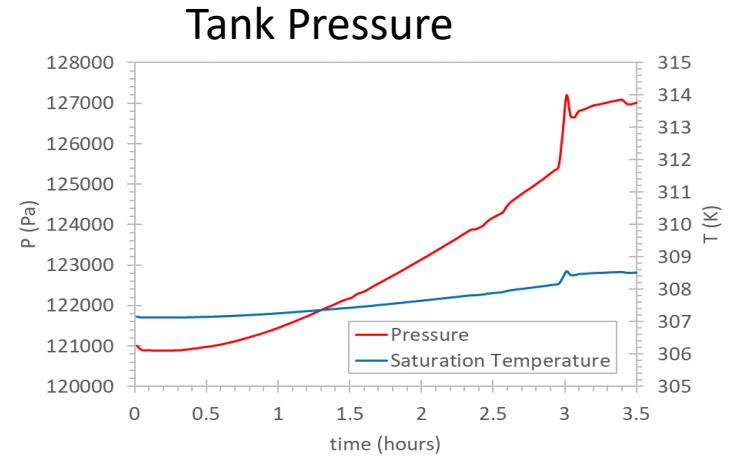
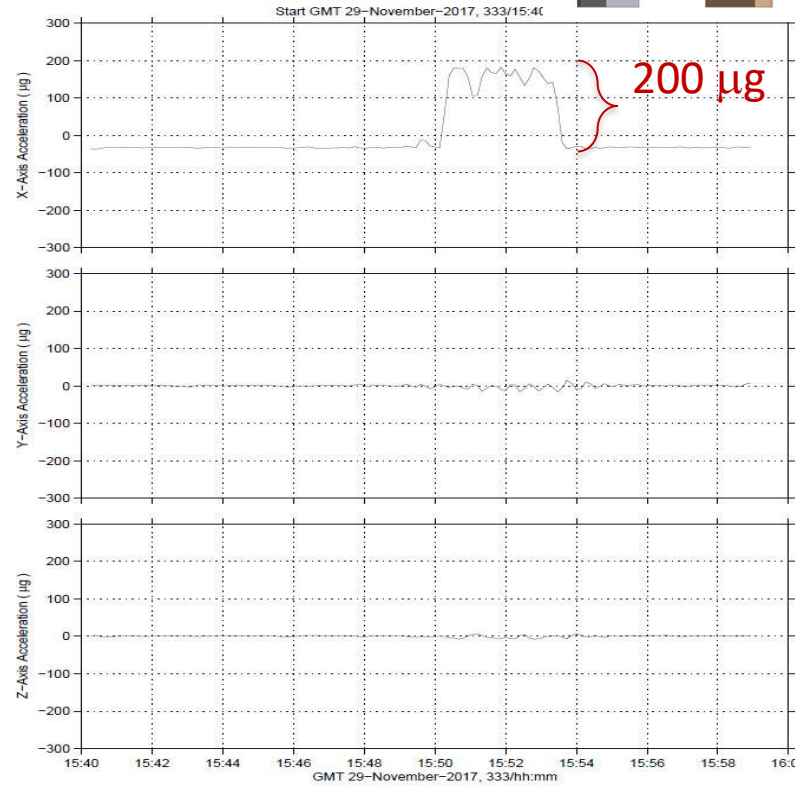
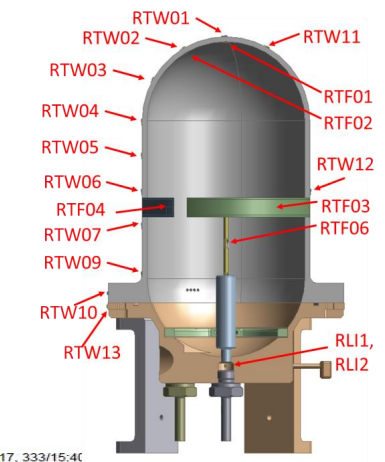
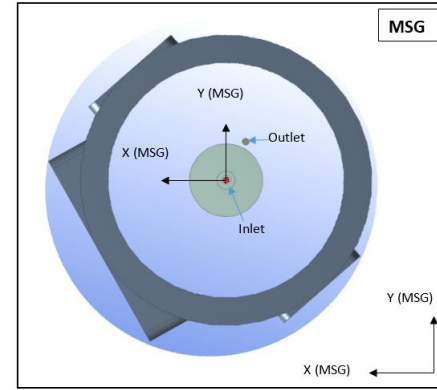
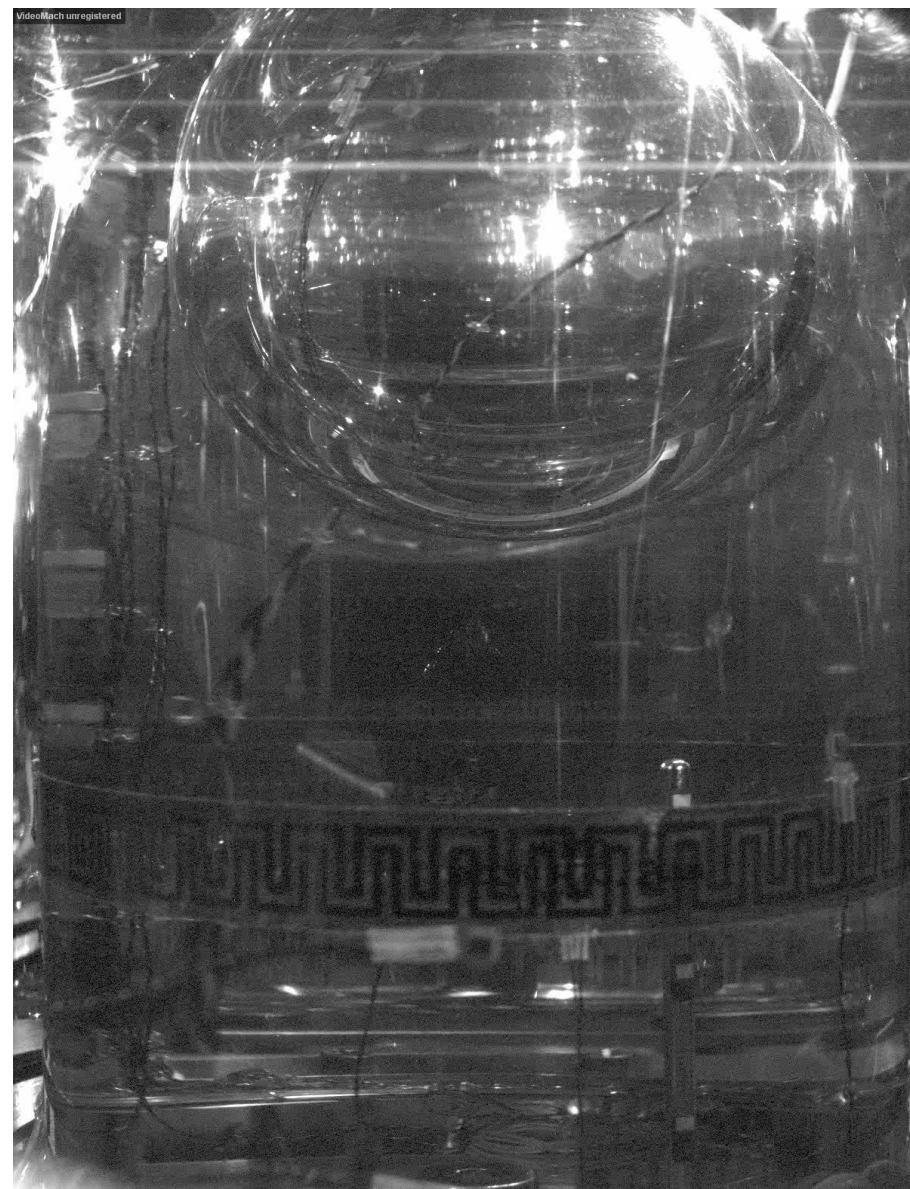
3f/s



Test 270: Thruster Acceleration FL = 90% (3D Asymmetry)



1f/s Test 301: ~20 min Reboost Acceleration in MSG +x direction



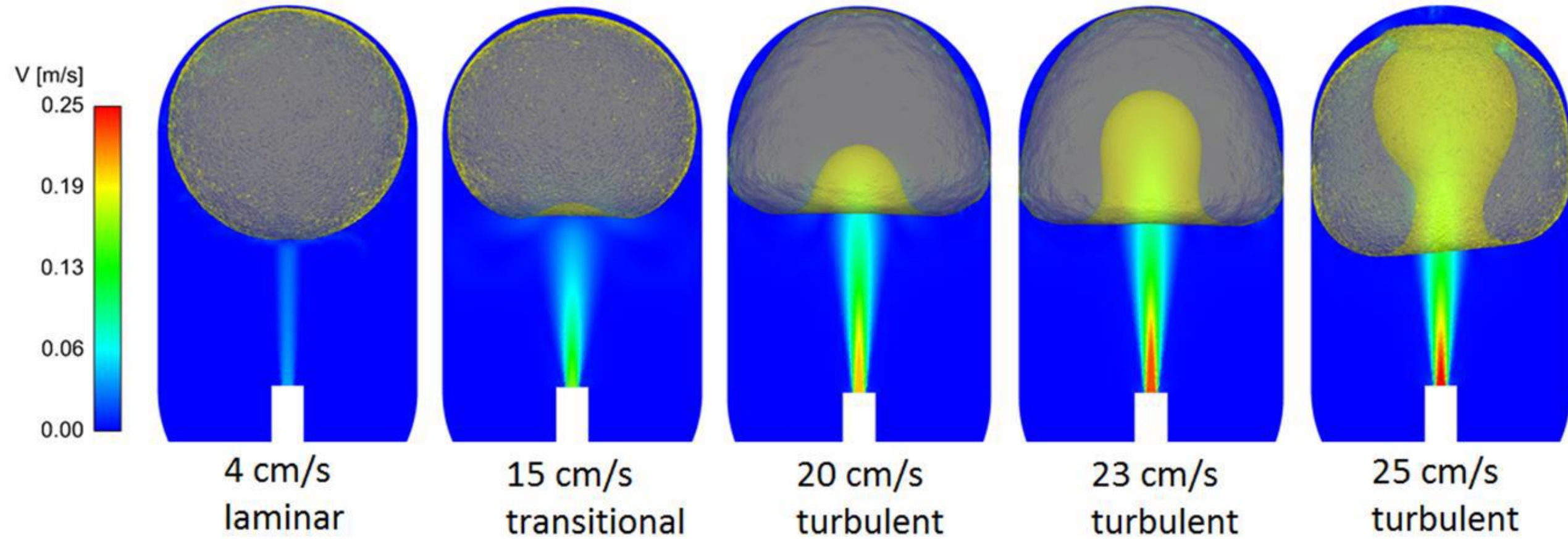


Isothermal Jet Mixing - Ullage – Jet Interaction

3D VOF Model Simulation of Jet Mixing & Ullage Penetration in Microgravity



Isothermal – No Phase Change - 70% Fill Level



Microgravity Isothermal Jet Mixing (No Phase Change)

35s 30 f/s

(#9) 6 cm/s Isothermal Jet



(#220) 15 cm/s Isothermal Jet



FL = 70%

$T_0 = 38\text{ C}$

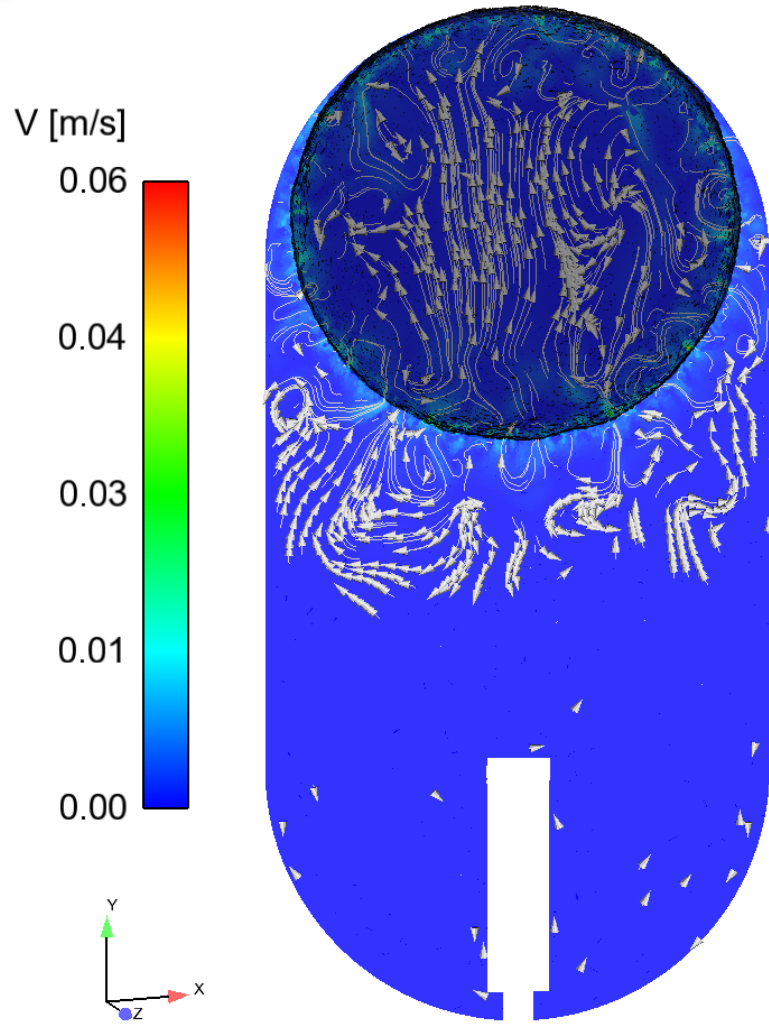
$T_{vj} = T_T$

$V_{jet} = 6, 15\text{ cm/s}$

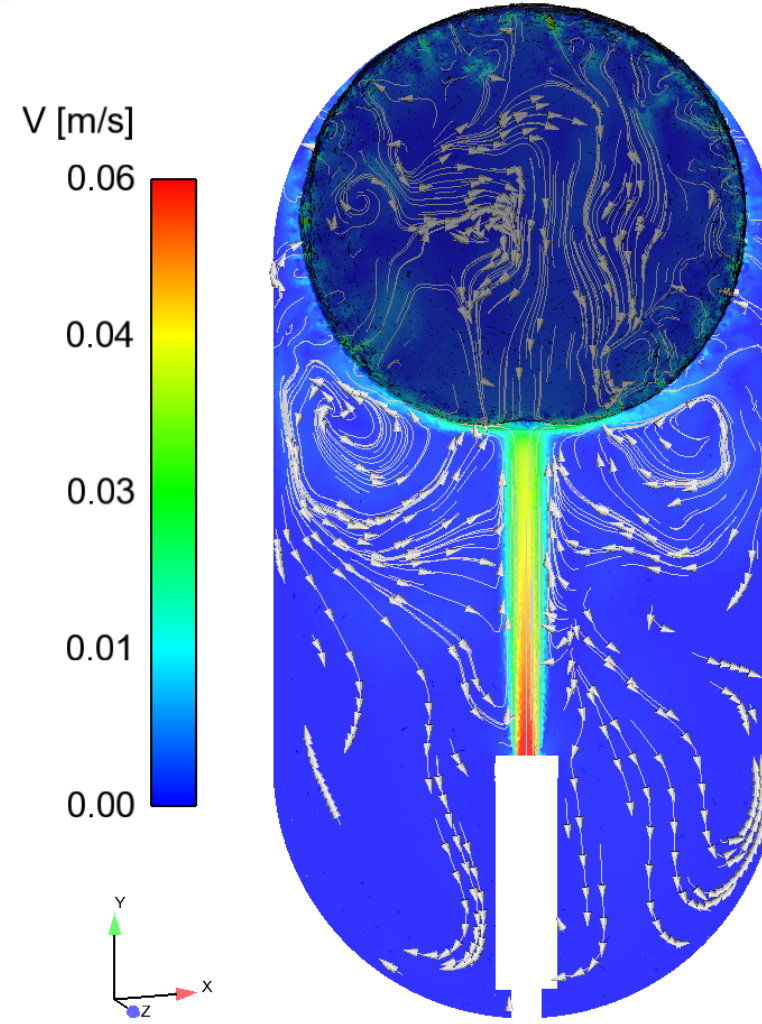
$T_{jet} = T_{outlet}$

- Microgravity **low flow** rate Jet-Ullage Interaction is non-intuitive as Ullage moves downward towards the Nozzle
- Microgravity **high flowrate** jet-ullage interaction intuitive and quite similar to previous numerical predictions

Jet Mixing Validation: Case 9 – 74%, 6 cm/s, Jet Angle 0 degrees



Beginning of mixing

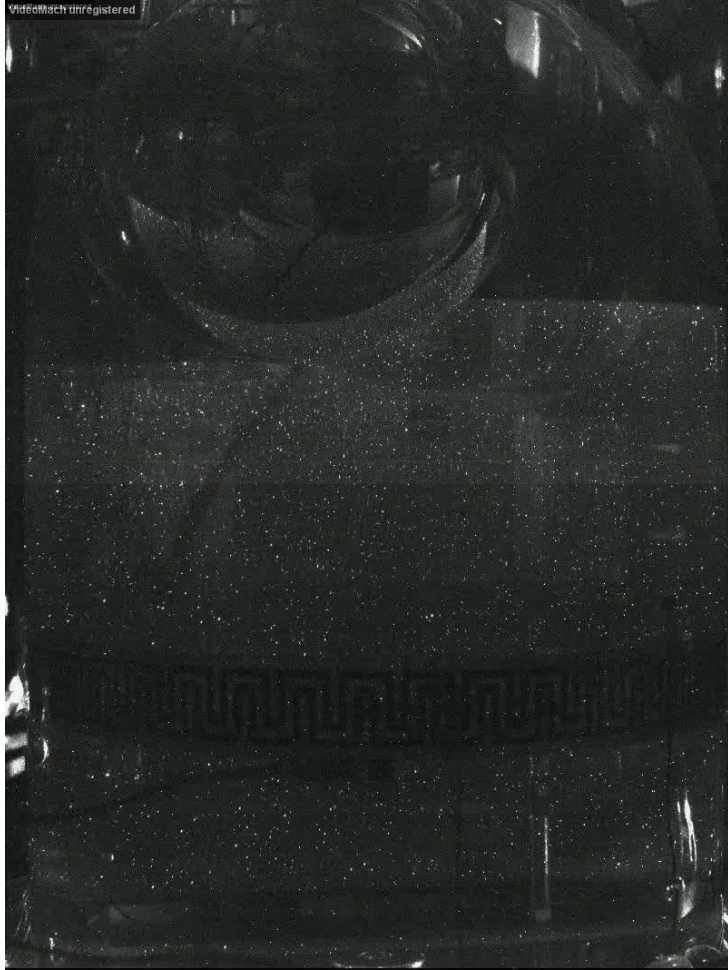


4 minutes of mixing

ZBOT Microgravity Jet Mixing at Jet V = 6, 10, and 20 cm/sec: PIV Results



DPIV 504 T_0 -2 K 6cm/s SubCooled Jet Mixing



DPIV Test # 504

$$T_{vj} = T_T$$

$$V_{jet} = 6 \text{ cm/s}$$

$$FL = 90\%$$

$$T_0 = 38 \text{ C}$$

DPIV #502 T_0 -1 K 10 cm/s SubCooled Jet Mixing



DPIV Test # 502

$$T_{vj} = T_T$$

$$V_{jet} = 10 \text{ cm/s}$$

$$FL = 90\%$$

$$T_0 = 38 \text{ C}$$

DPIV #500 T_0 -1 K 20 cm/s SubCooled Jet Mixing



DPIV Test # 500

$$T_{vj} = T_T$$

$$V_{jet} = 20 \text{ cm/s}$$

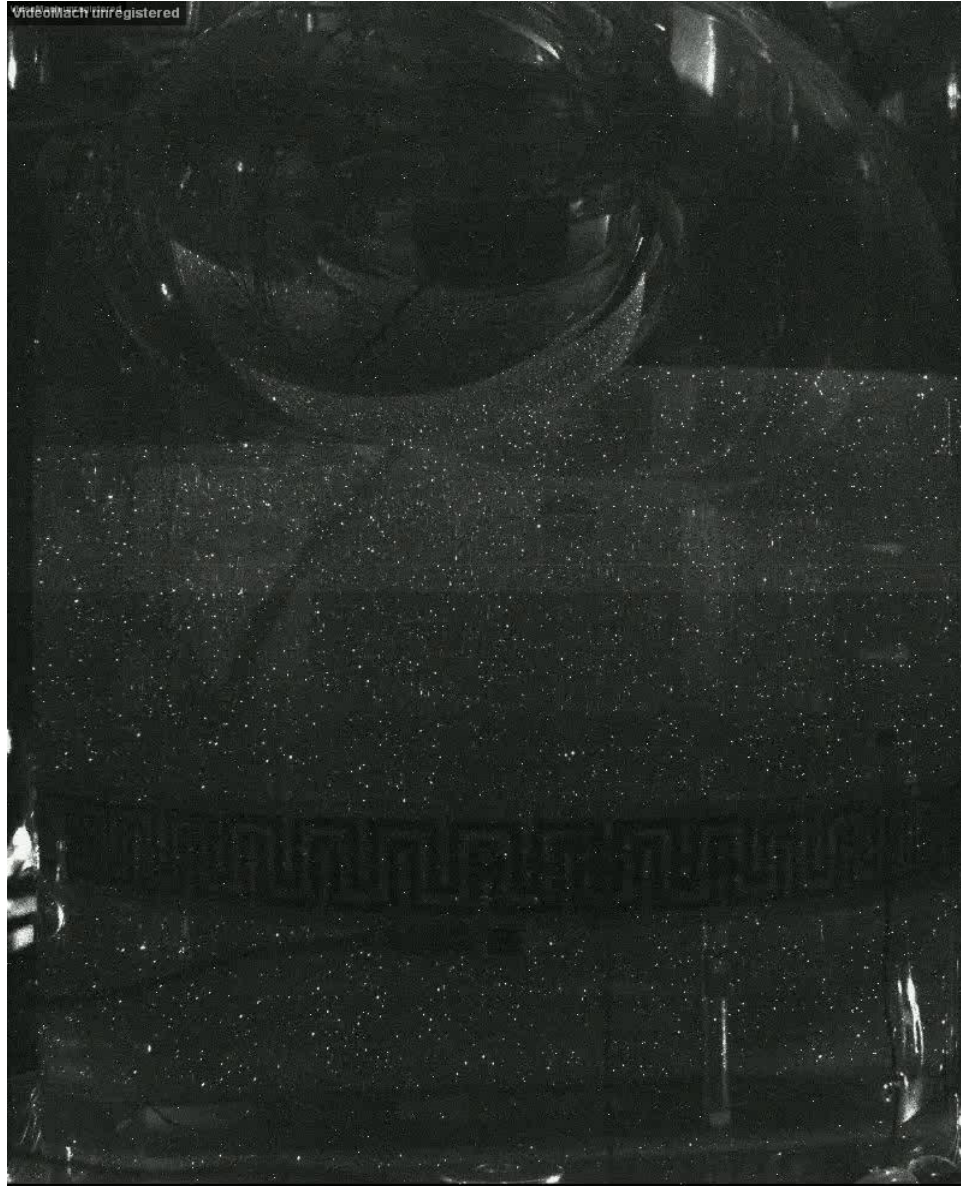
$$FL = 90\%$$

$$T_0 = 38 \text{ C}$$

Microgravity Jet Mixing at Jet $V = 6$ cm/sec: Particle Streak Imaging Results



504 T_0 -2 K 6cm/s SubCooled Jet Mixing



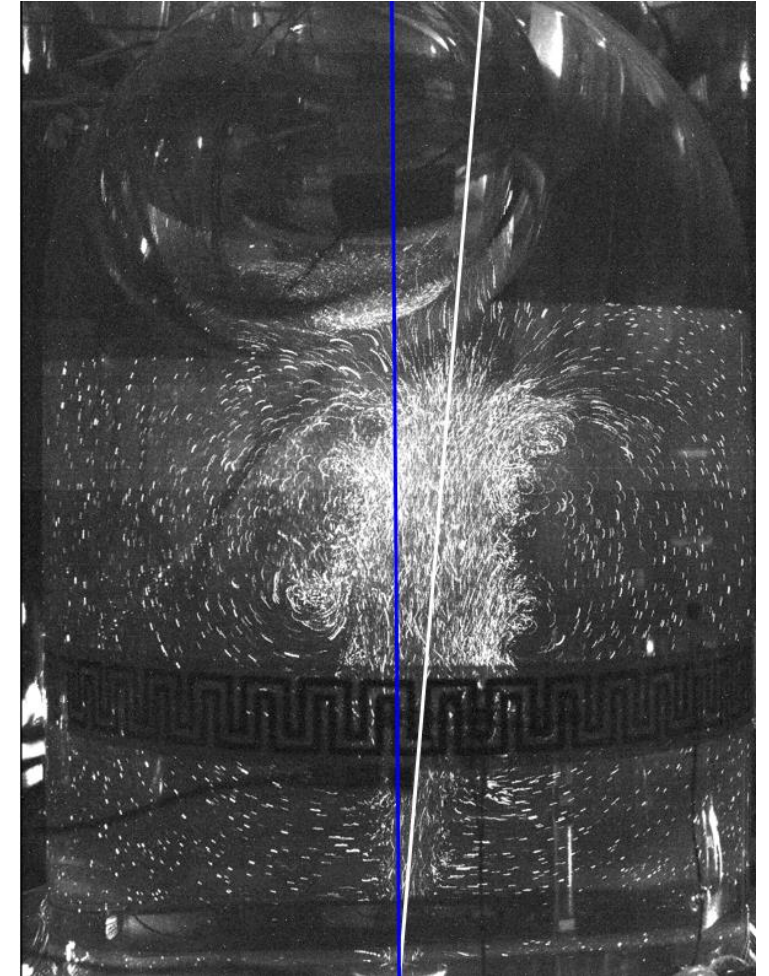
DPIV Test # 504

$$T_{vj} = T_T$$

$$V_{jet} = 6 \text{ cm/s}$$

$$FL = 90\%$$

$$T_0 = 38 \text{ C}$$

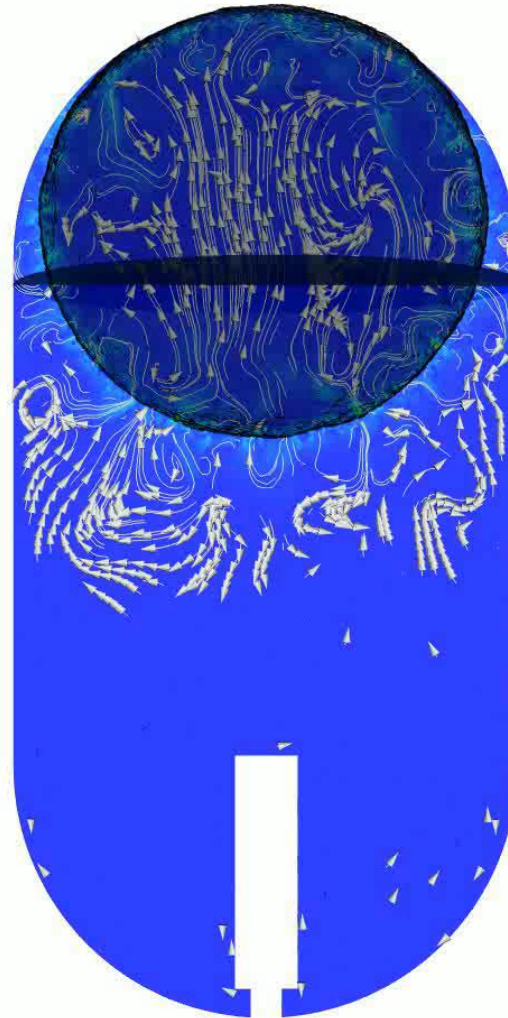
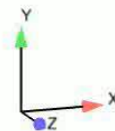


Jet Mixing Validation: Case 9 - 74%, 6 cm/s, Jet Angle 5 degrees



VideoMach unregistered

V [m/s]



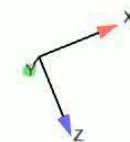
Front view

ZBOT Validation
Case 9 5deg-side jet angle
73.87% fill ratio
6 cm/s jet speed
 T_{outlet} jet temperature



Top view

Time = 60.0 [s]



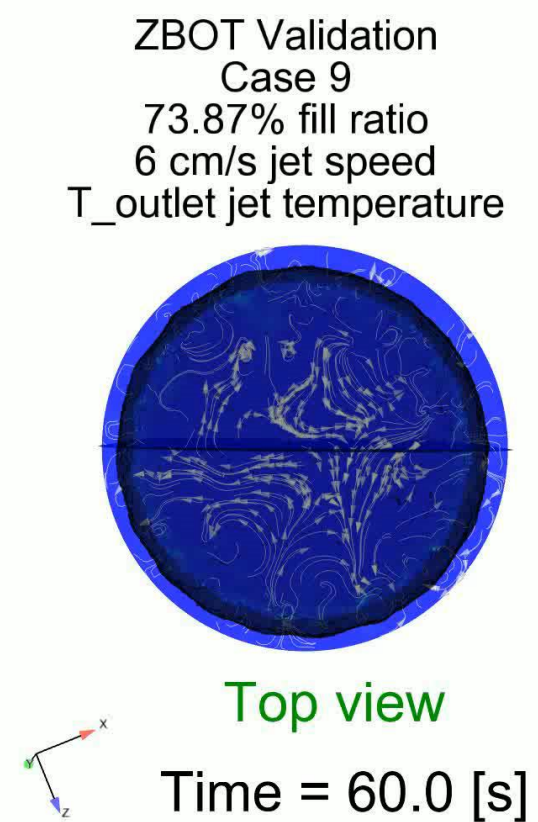
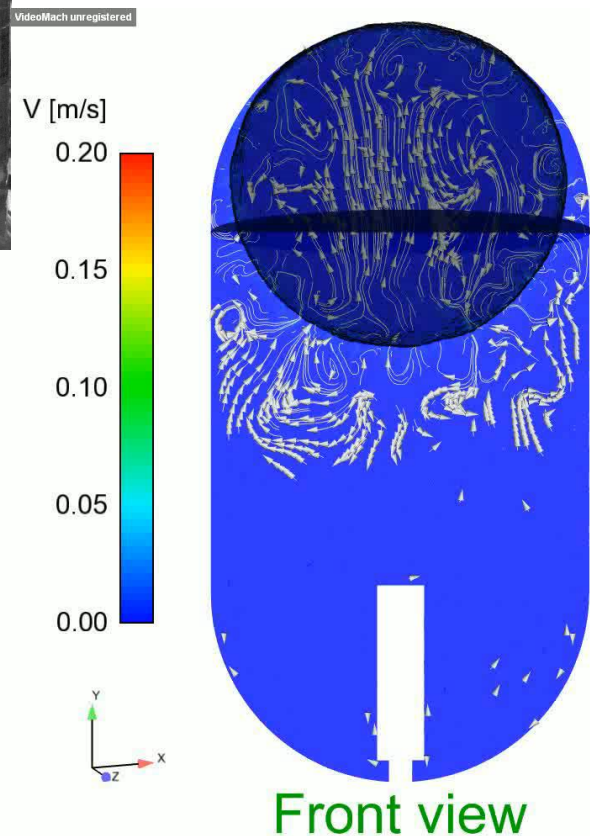
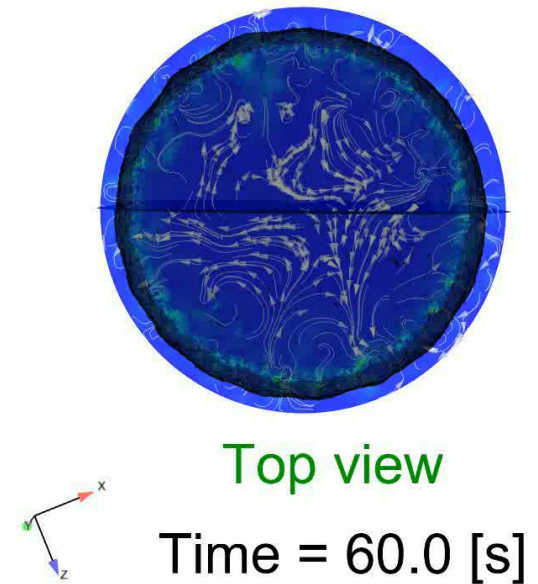
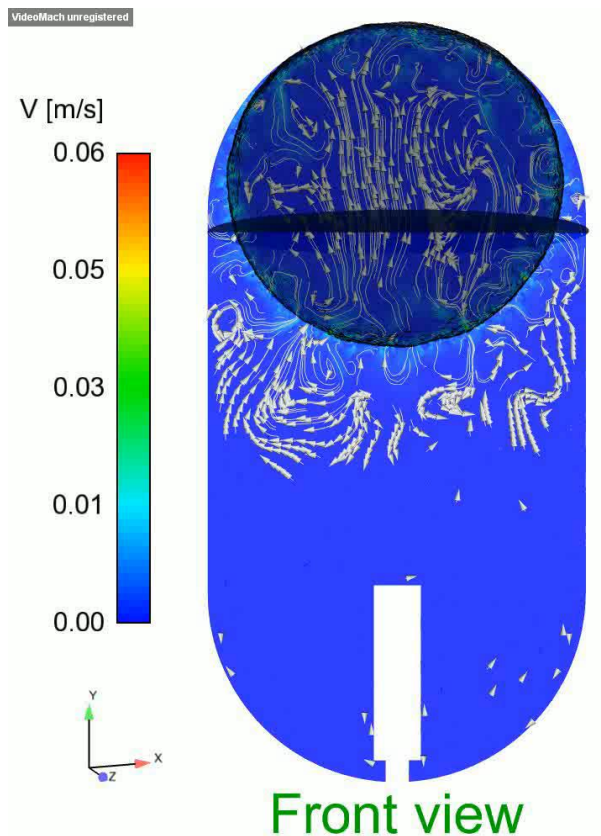
ZBOT – Case 9: Microgravity Low Velocity Isothermal Jet Mixing



Fill Ratio: 73.87%
Jet Speed: 6 cm/s
Jet Temperature = $T_{\text{Tank_Outlet}}$

Straight Jet Flow

Slanted Jet Flow (5°)



ZBOT Validation
Case 9
73.87% fill ratio
6 cm/s jet speed
 T_{outlet} jet temperature

Jet Mixing Validation: Case 27 - 70%; 25 cm/s, Jet Angle 5 degrees



V [m/s]

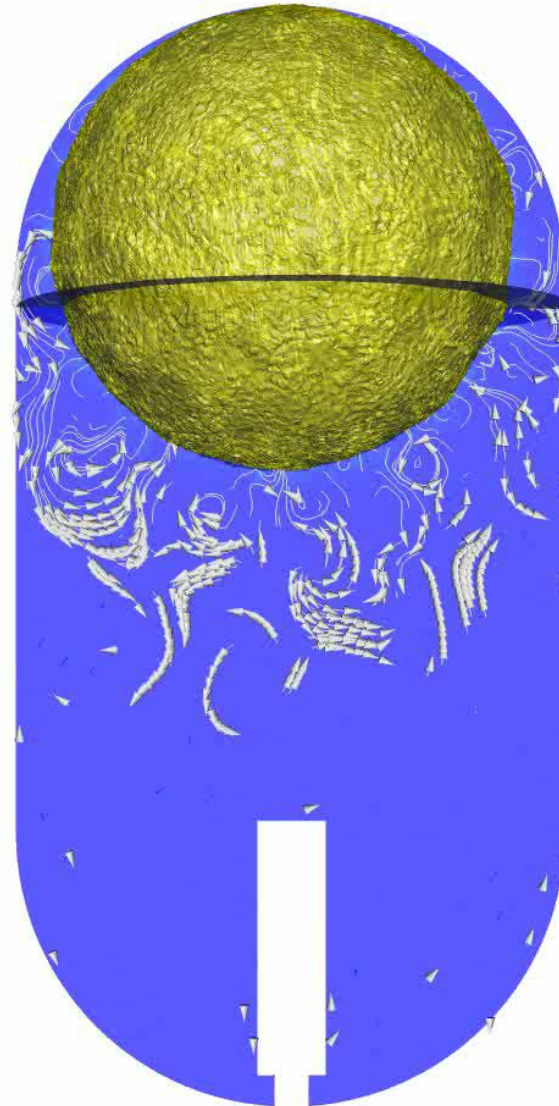
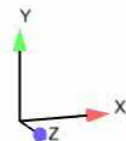
0.20

0.15

0.10

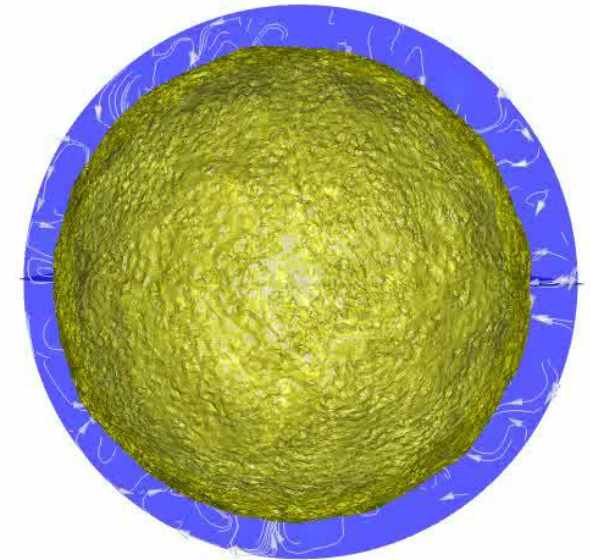
0.05

0.00



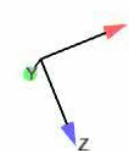
Front view

ZBOT Validation
Case 27 Jet-Angle 5-front 5-side
77.26% fill ratio
25 cm/s jet speed
T_{outlet} jet temperature

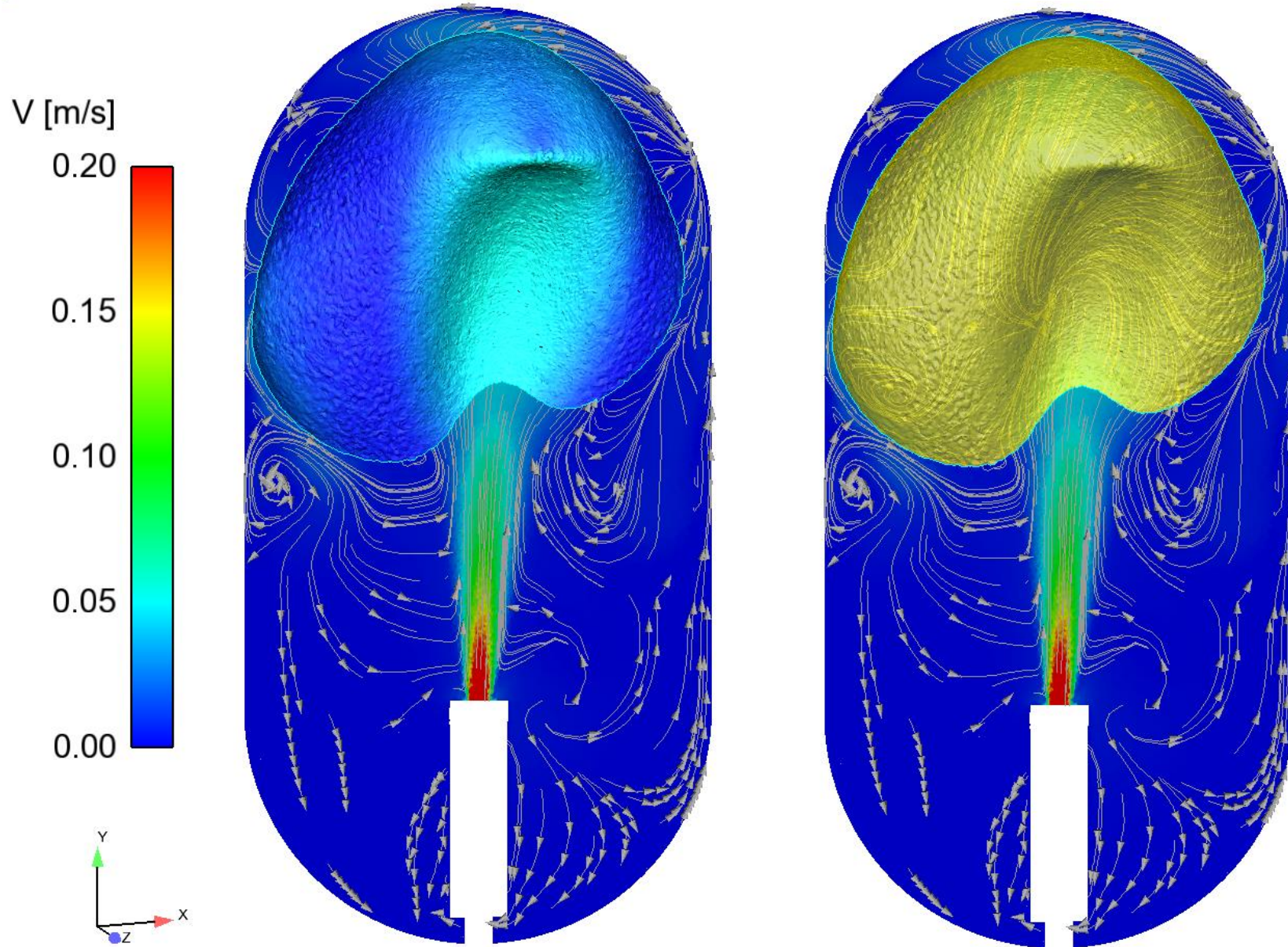


Top view

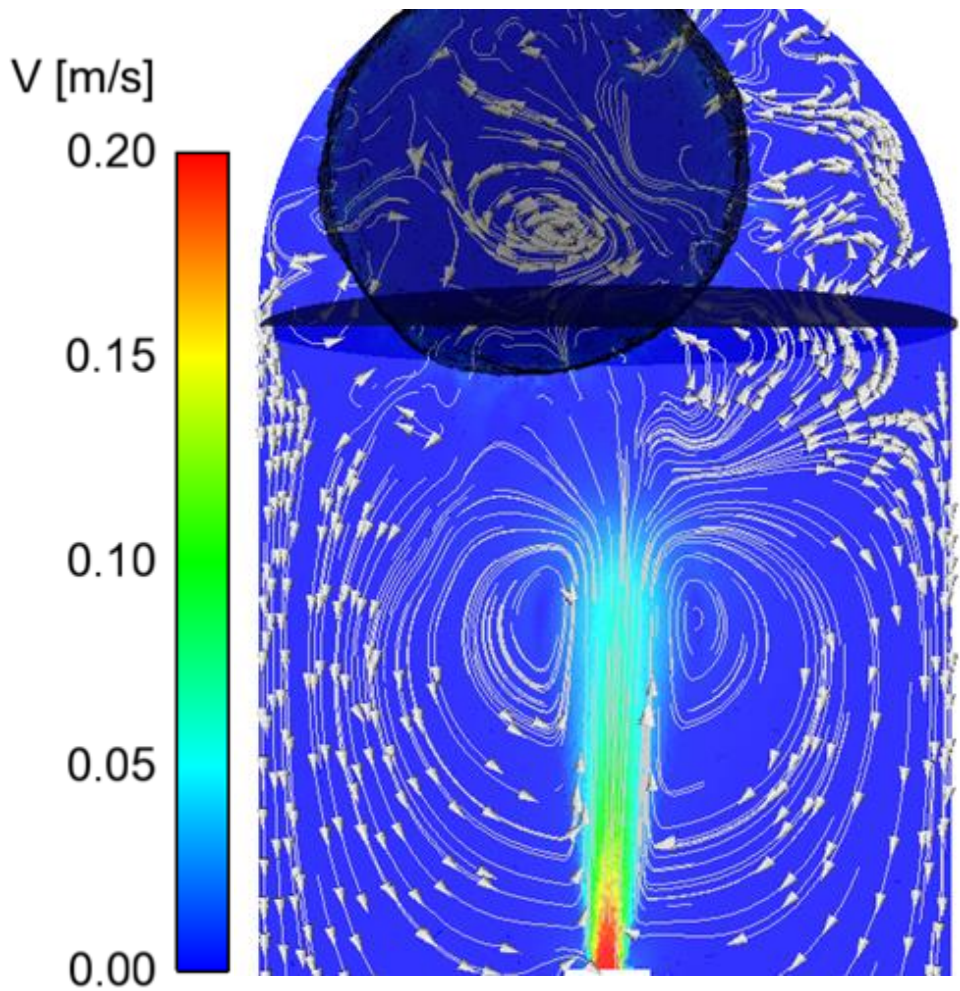
Time = 60.0 [s]



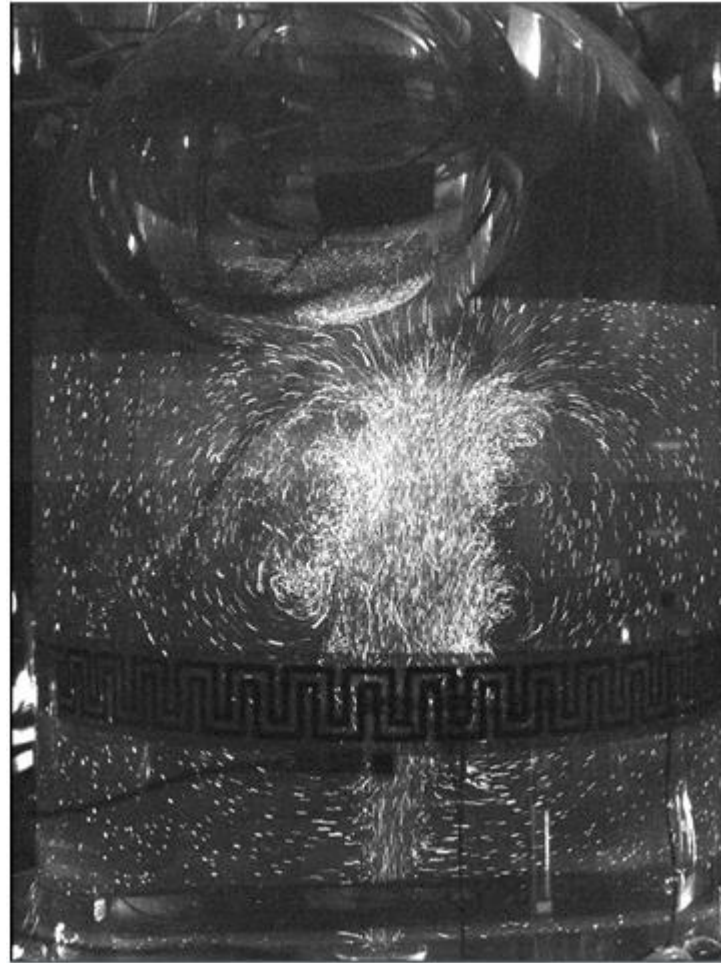
Jet Mixing Validation: Case 27 - 70%; 25 cm/s, Jet Angle 5 degrees



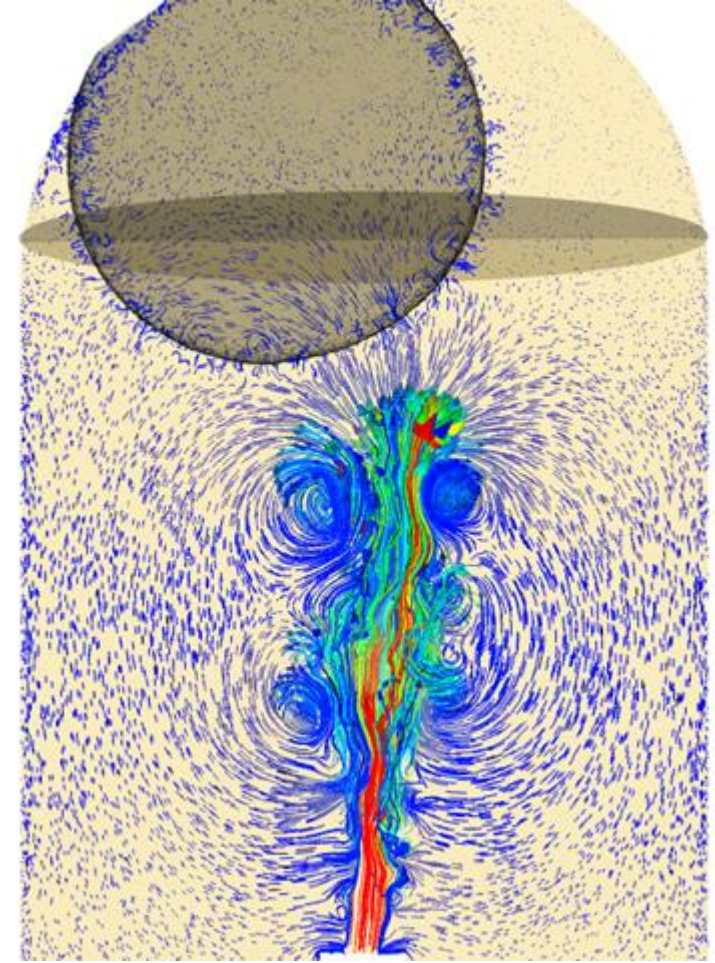
Case 256/500 – 91.32% fill, 20 cm/s jet speed, T0-1 jet temperature



RANS



Experiment



LES

Time = 1.2 [s]

Case 27 – 77.26% fill, 25 cm/s jet speed, T_outlet jet temperature



V [m/s]

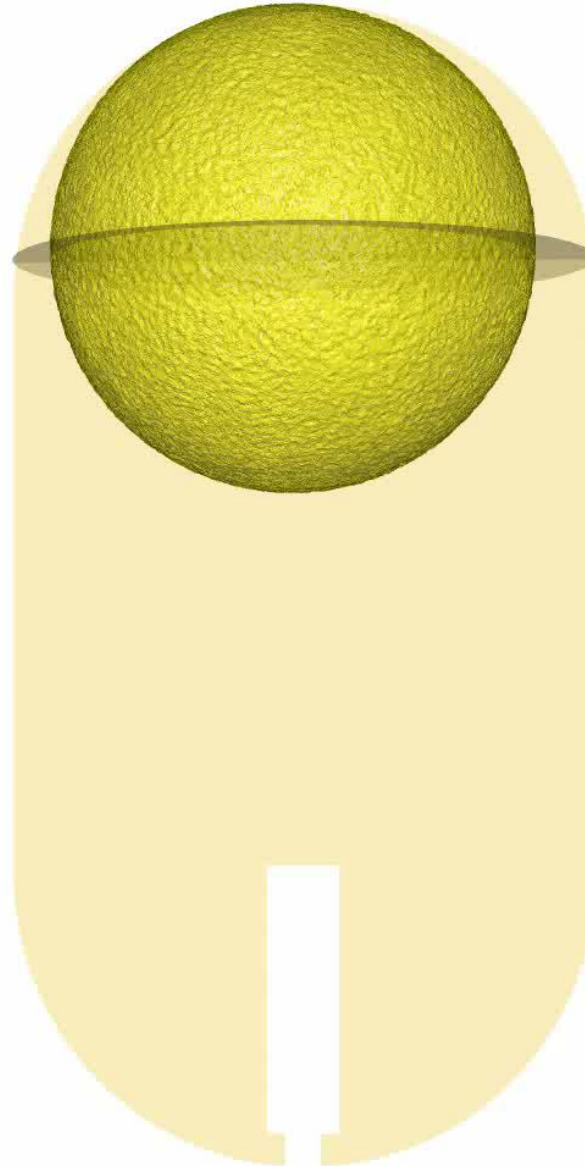
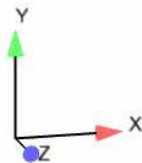
0.25

0.19

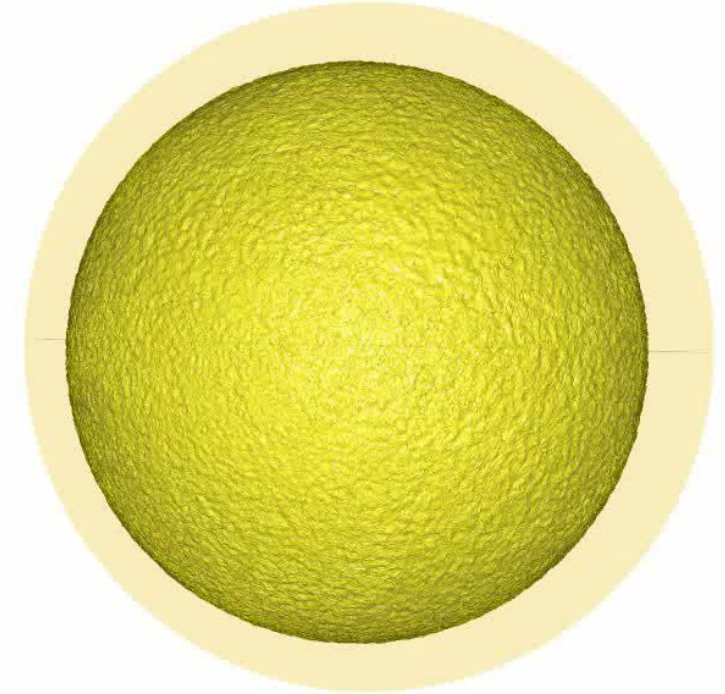
0.12

0.06

0.00

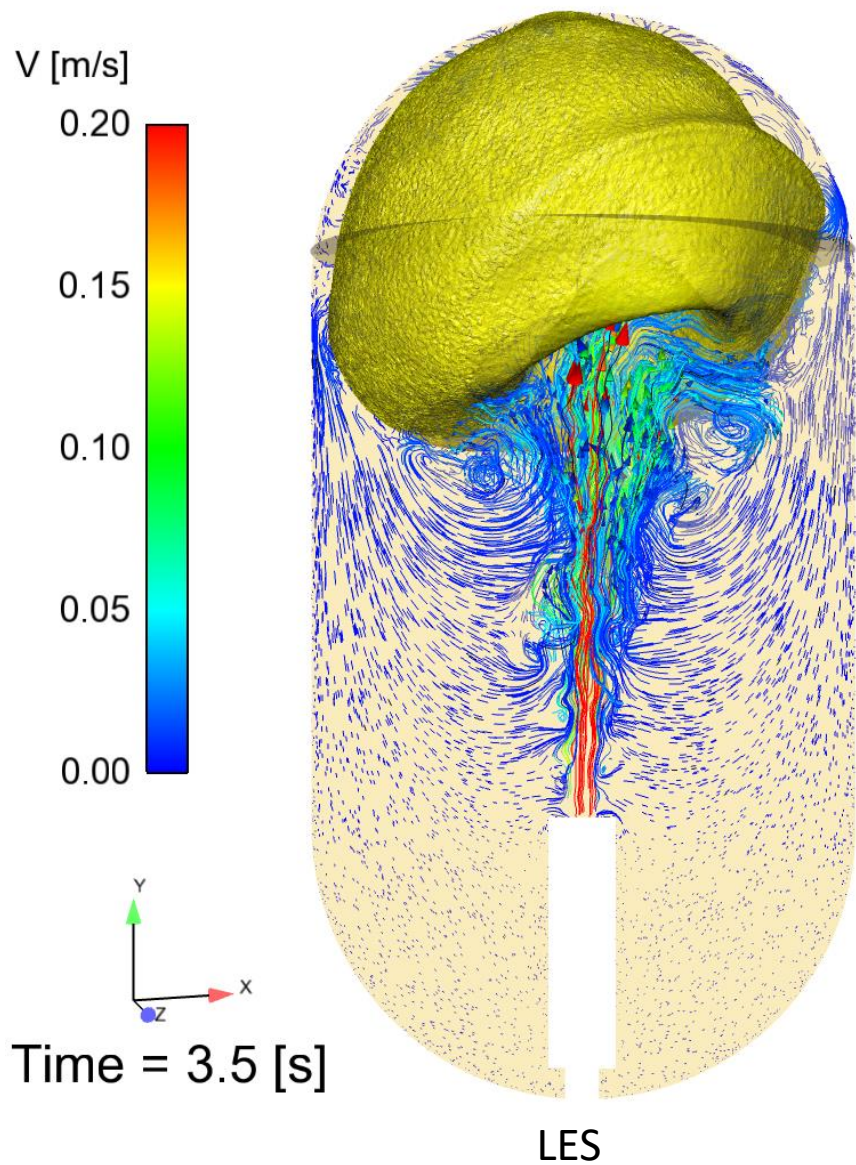


ZBOT Case 27
25 cm/s
LES

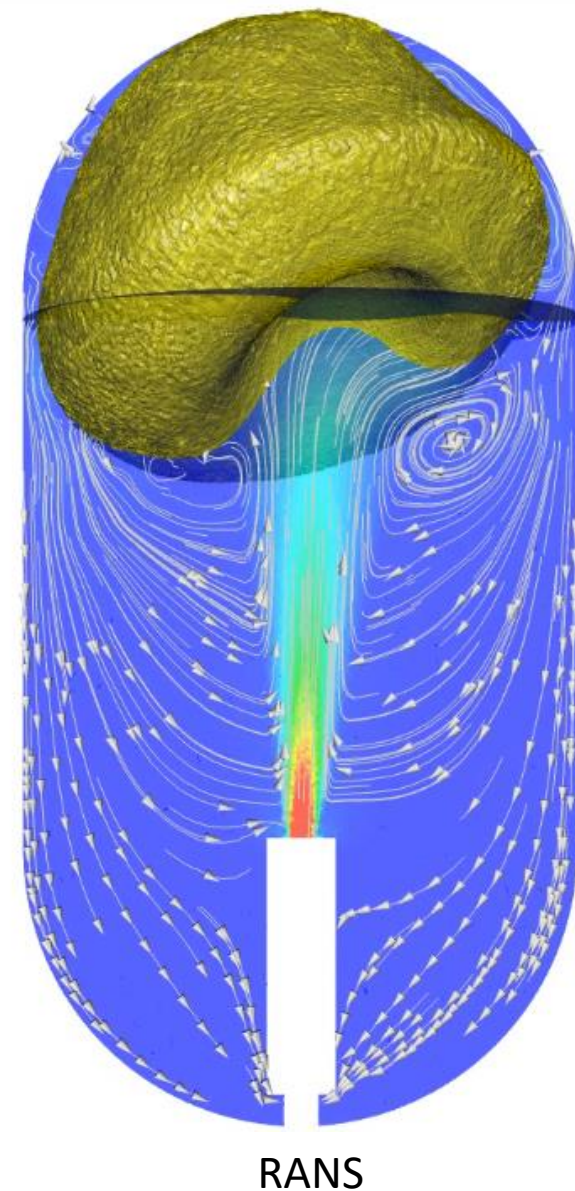


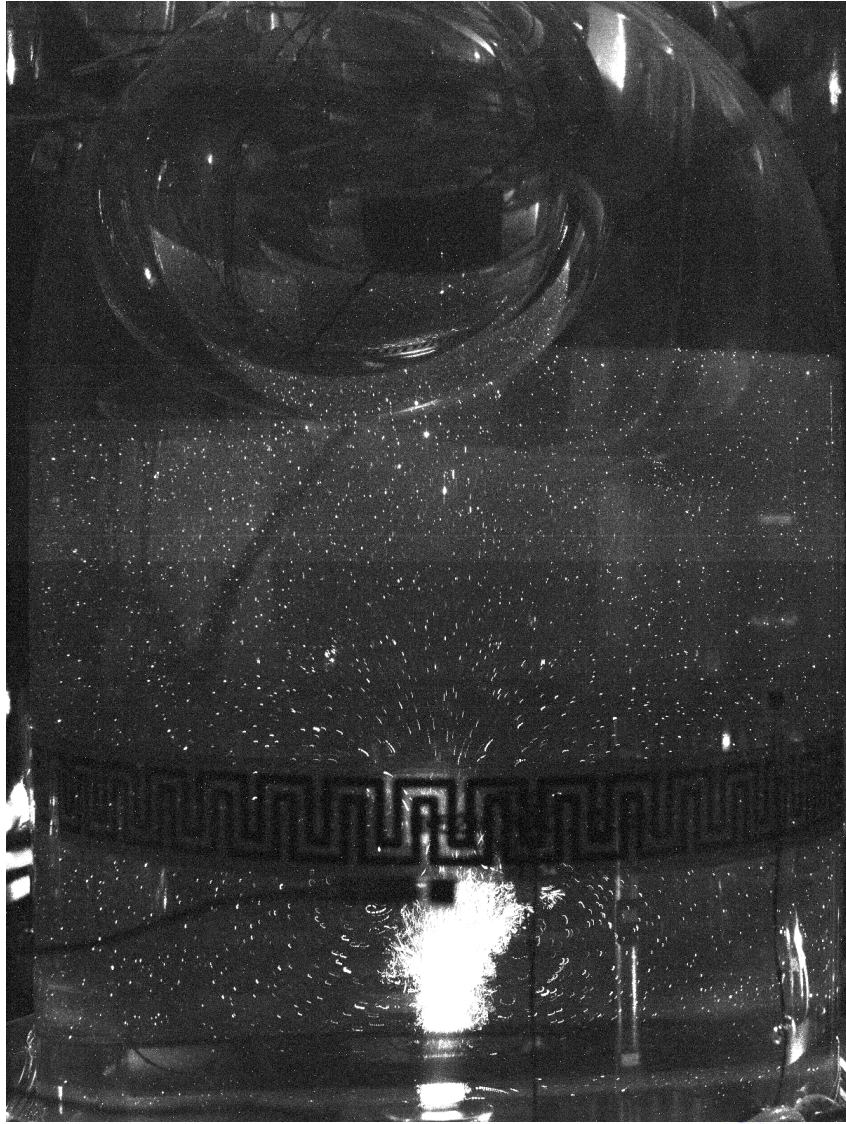
Time = 0.0 [s]

Case 27 – 77.26% fill, 25 cm/s jet speed, T_outlet jet temperature

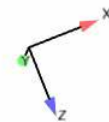
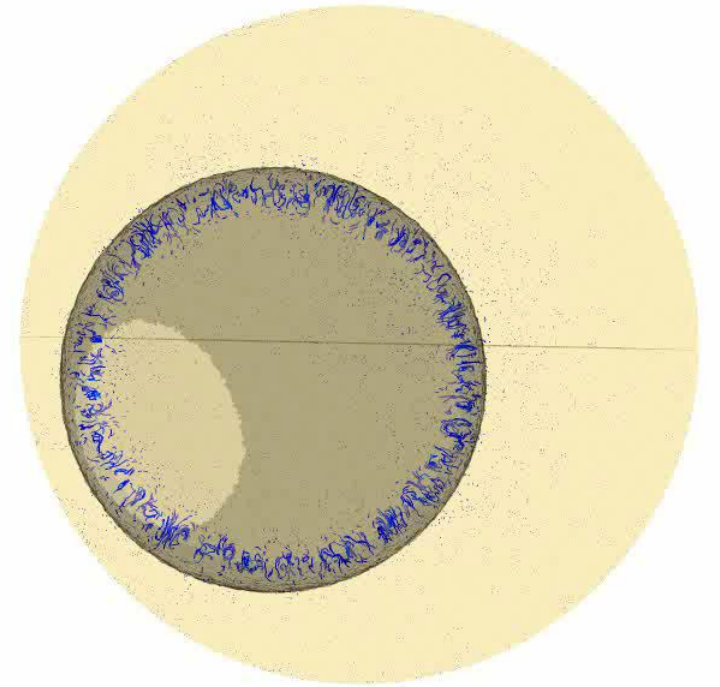
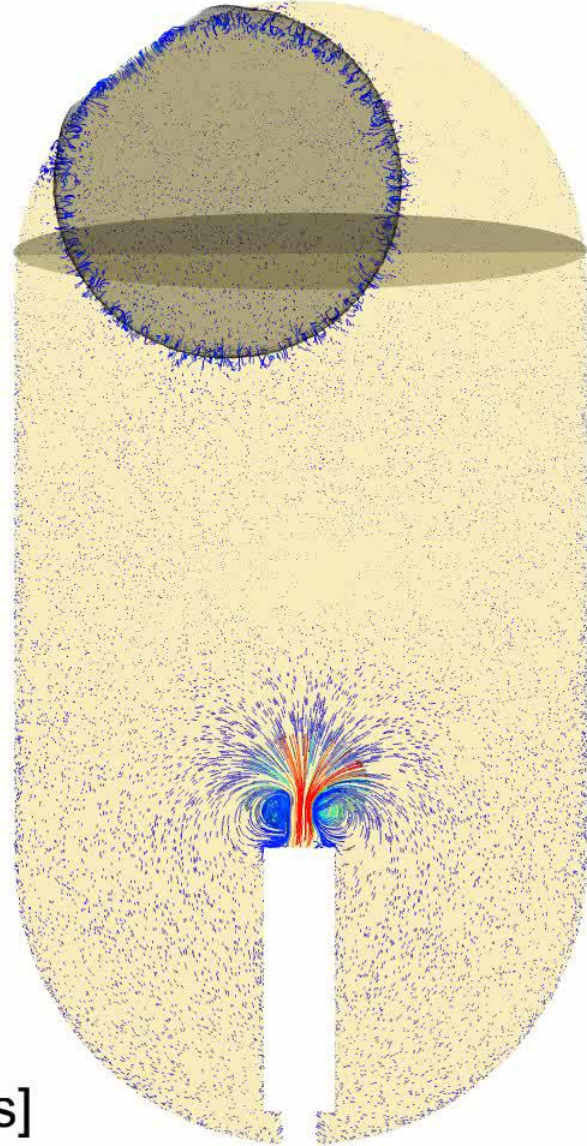


Experiment-4s

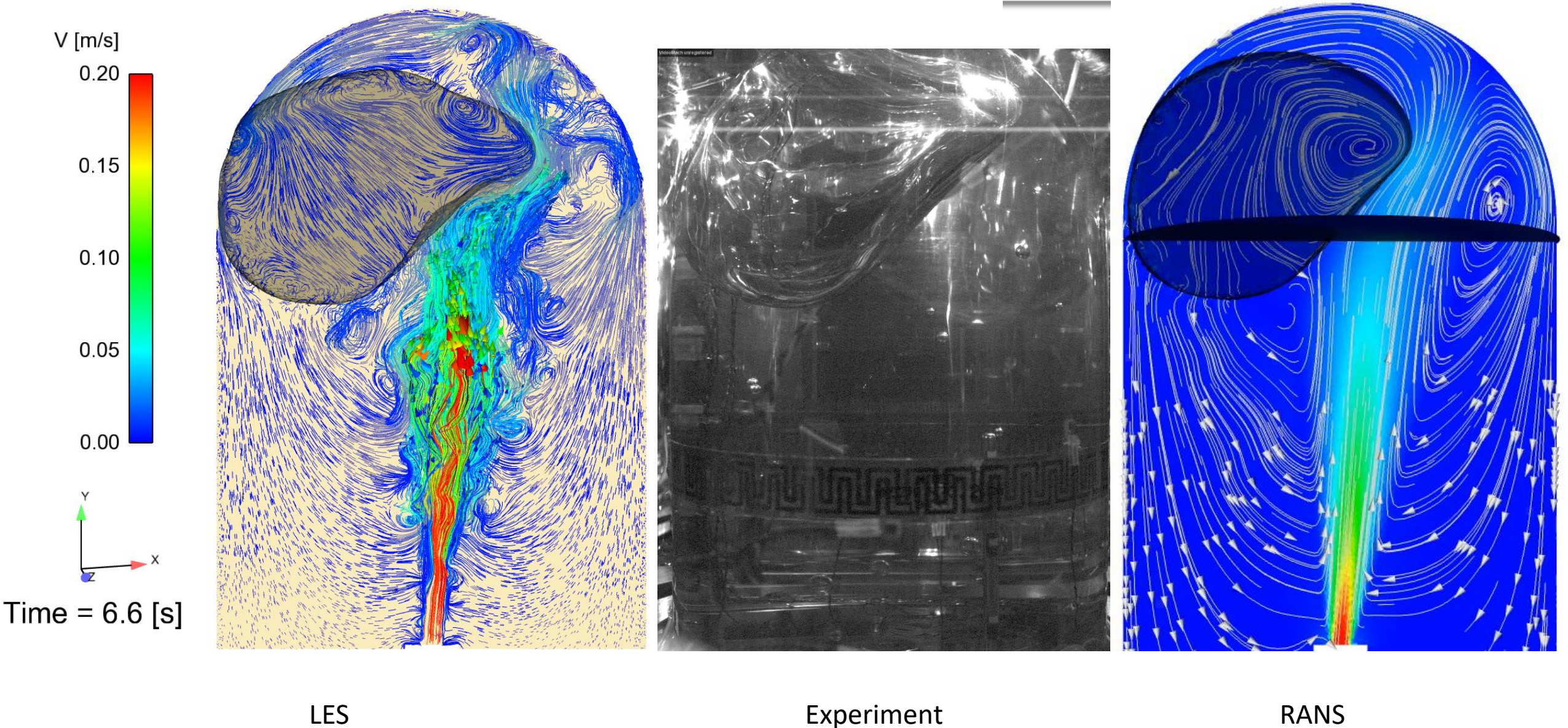




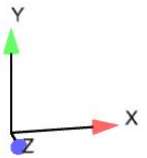
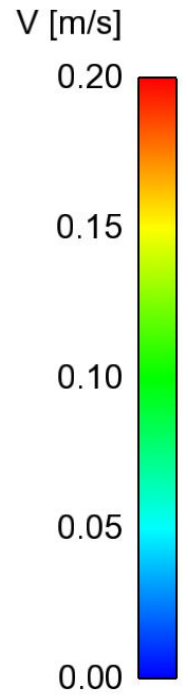
Time = 0.1 [s]



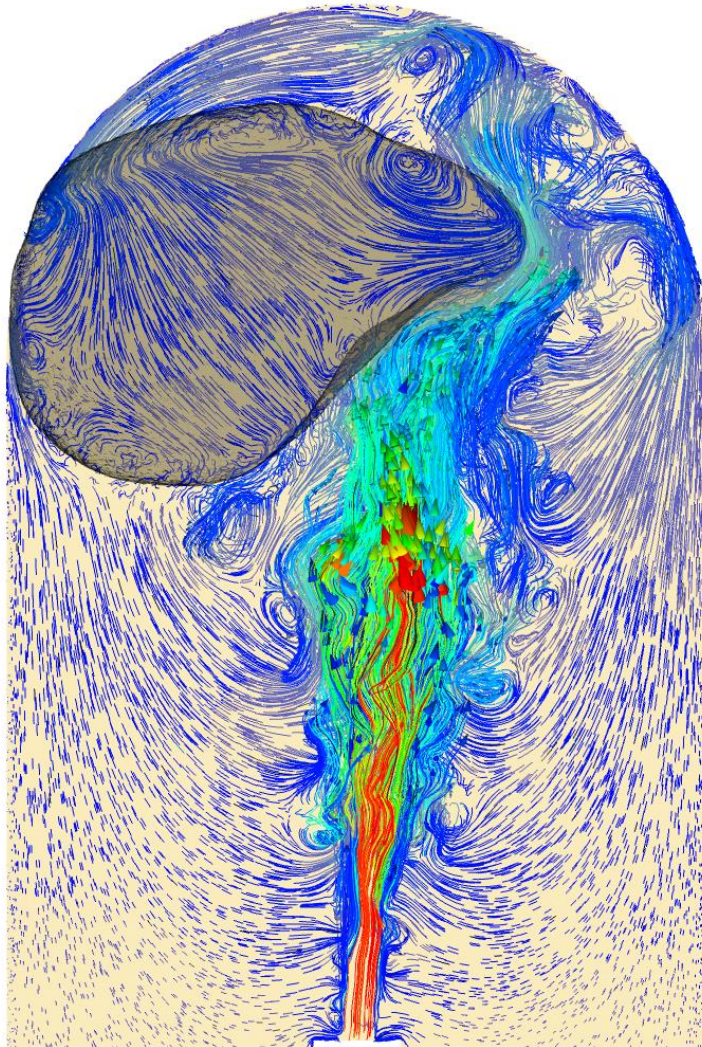
Case 256/500 – 91.32% fill, 20 cm/s jet speed, T0-1 jet temperature



Case 256/500 – 91.32% fill, 20 cm/s jet speed, T0-1 jet temperature



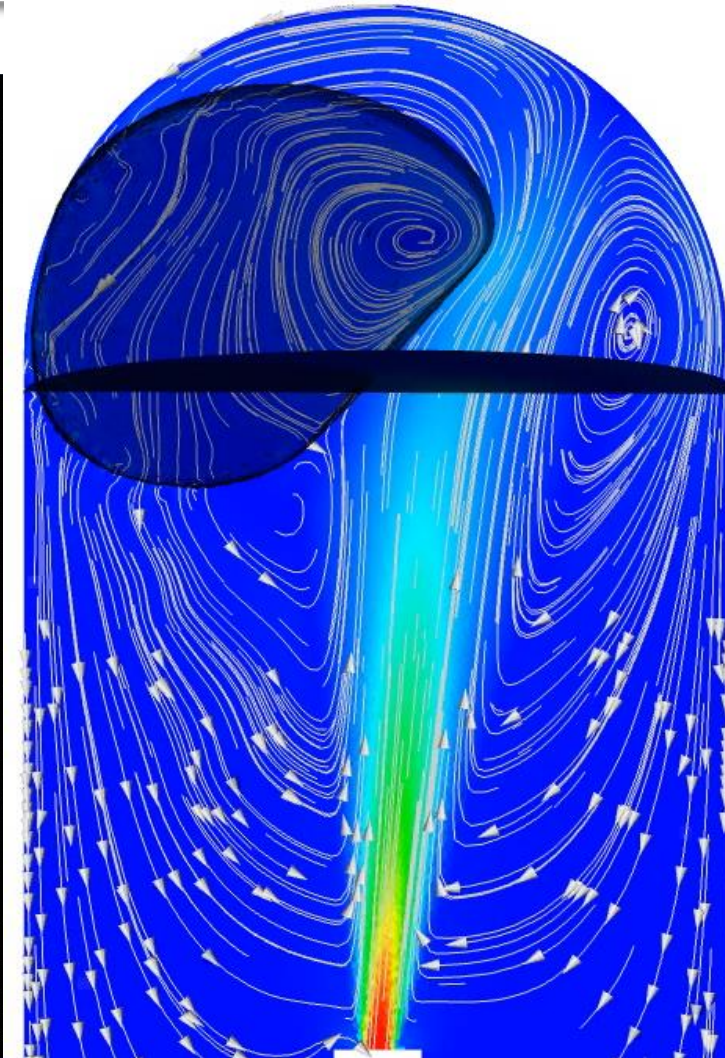
Time = 6.6 [s]



LES



Experiment

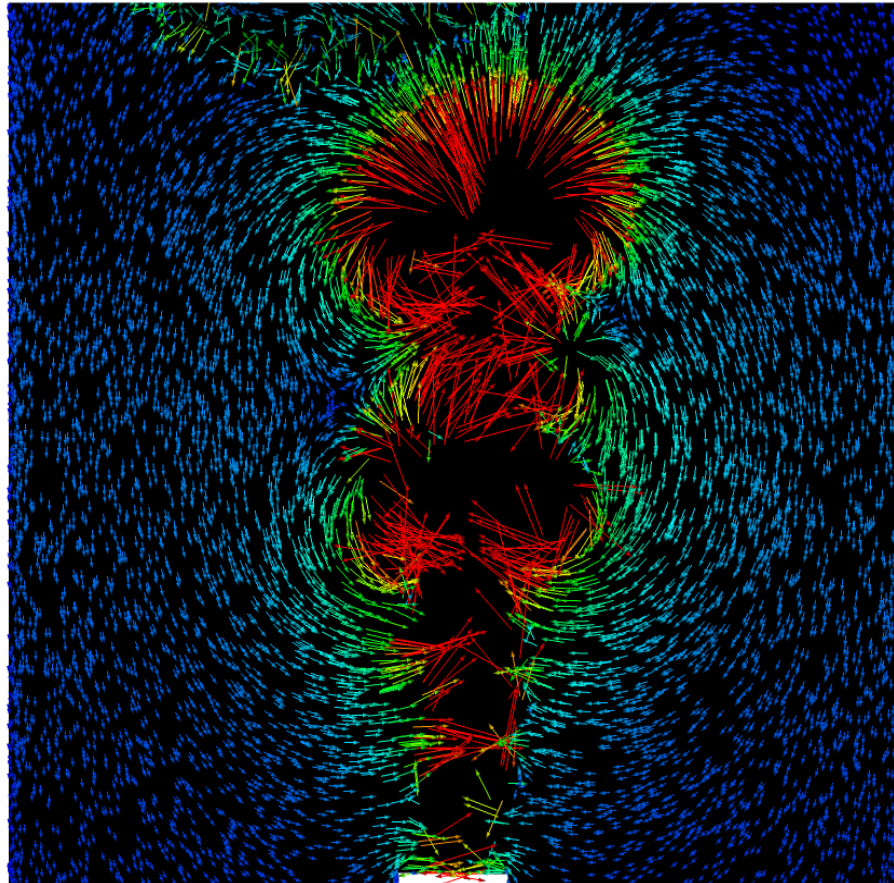


RANS

PIV Validation: Case 256/500 – 91.32% fill, 20 cm/s jet speed, T0-1 jet temperature

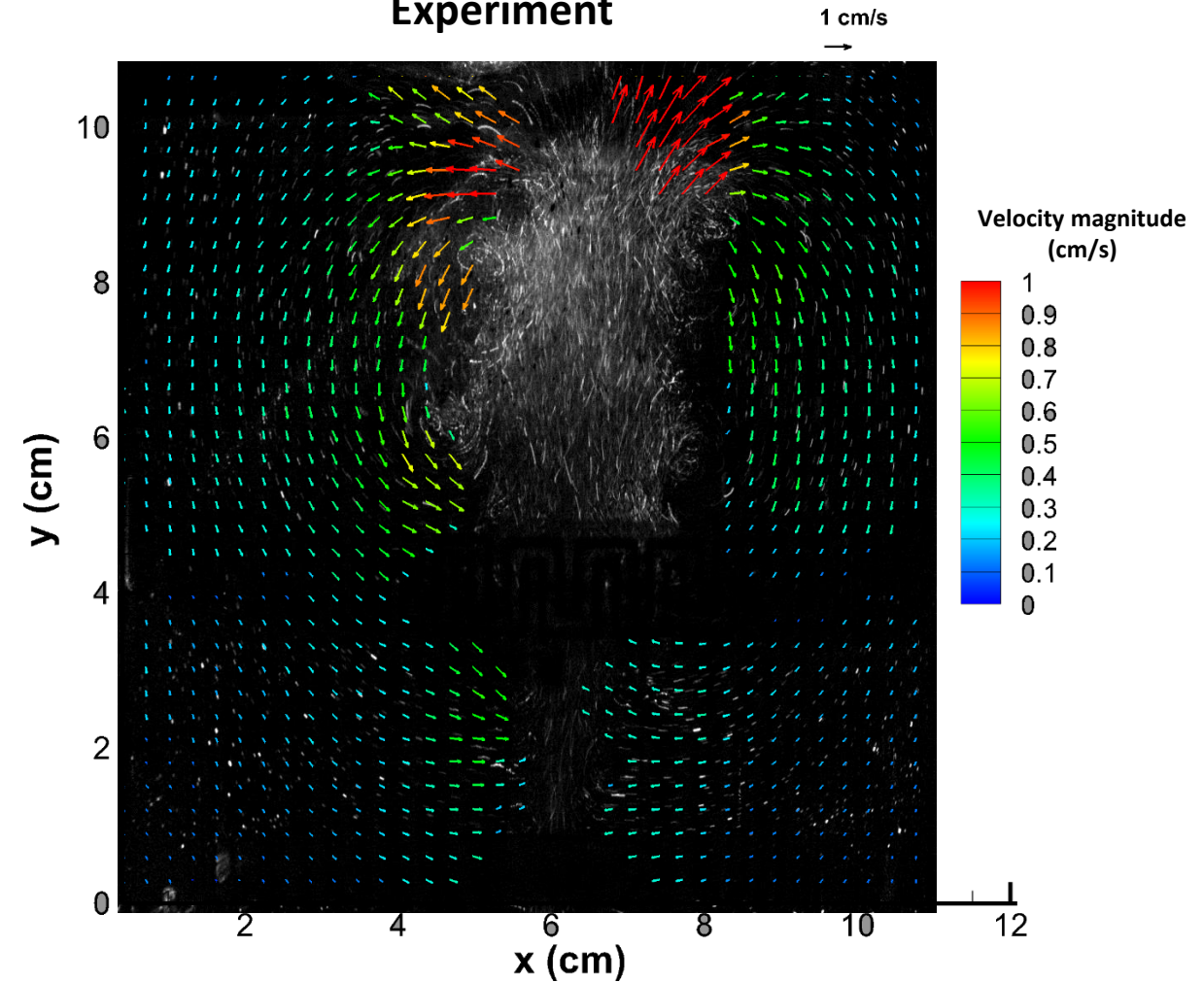


LES Simulation



Time = 1.2 [s]

Experiment





Subcooled Jet Mixing Pressure Control

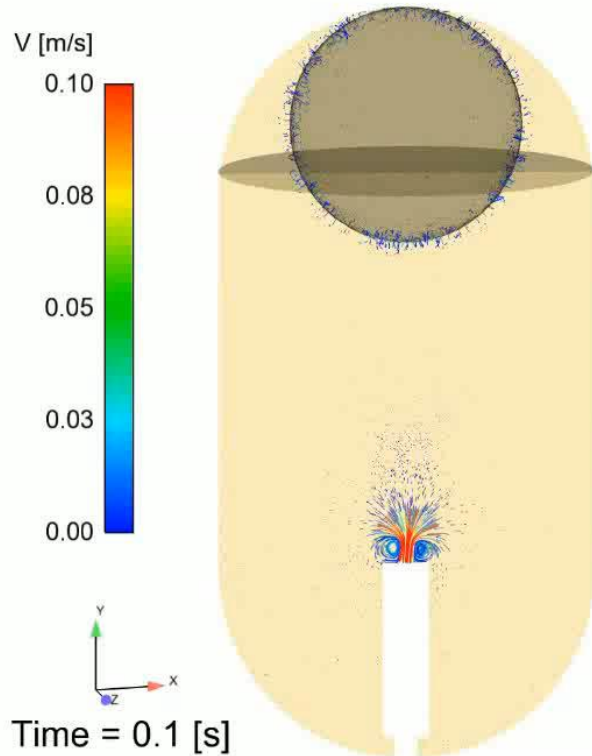
ZBOT Case 254: 90.62% fill level, 10 cm/s jet speed, T0-1 jet Temp

- Particle Streak Imaging Results

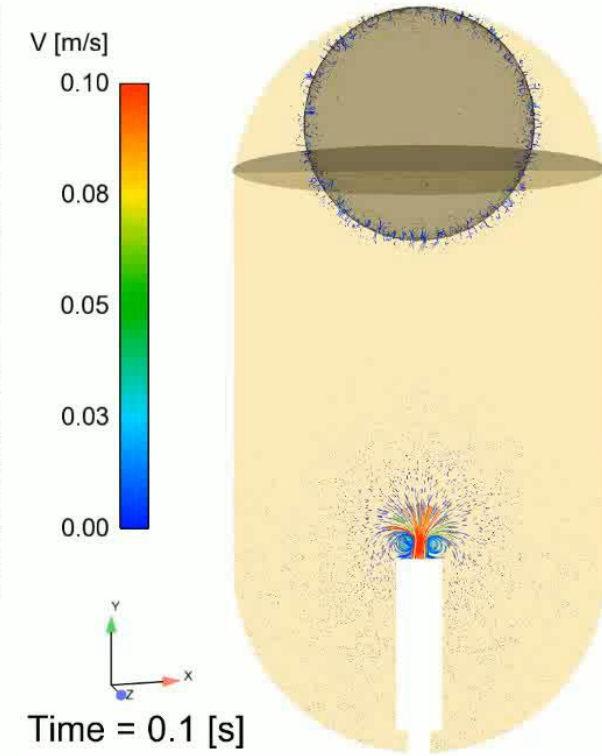
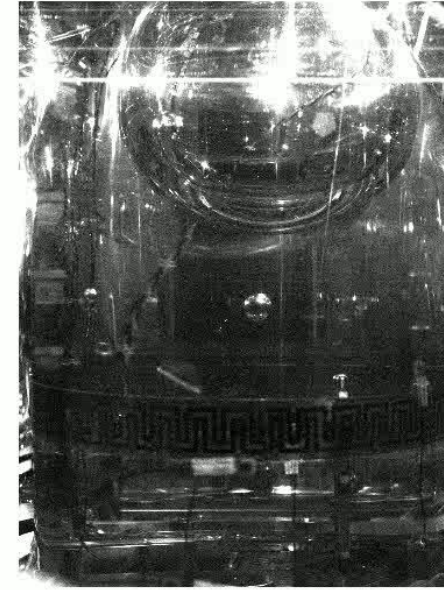
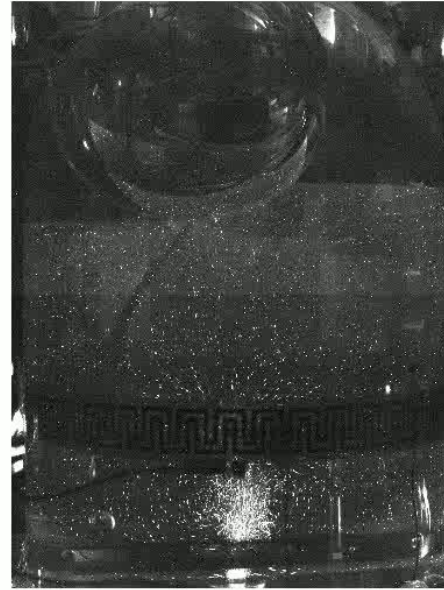


VideoMach unregistered

Comparison of LES and RANS simulations against PIV and white light imaging

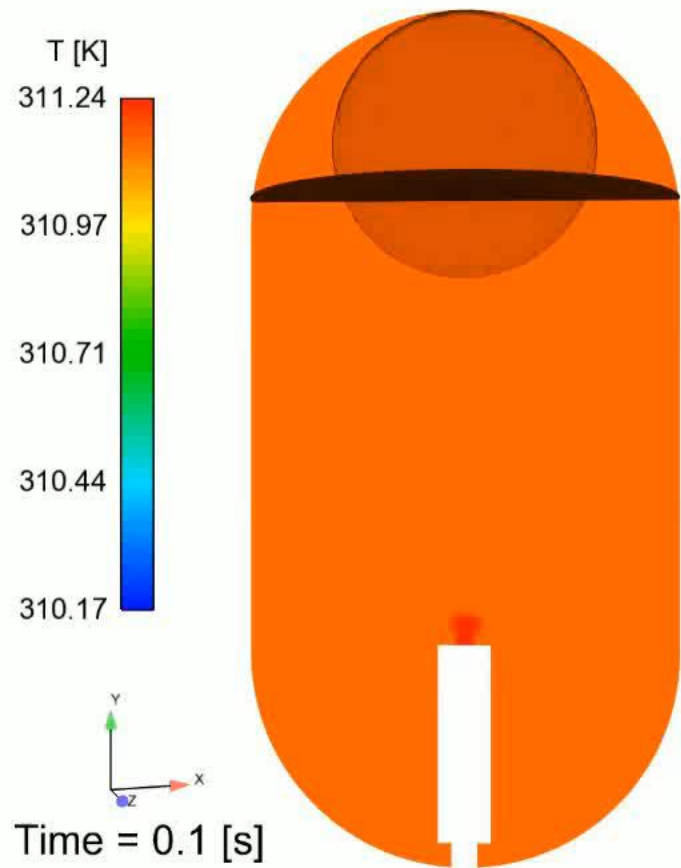


RANS

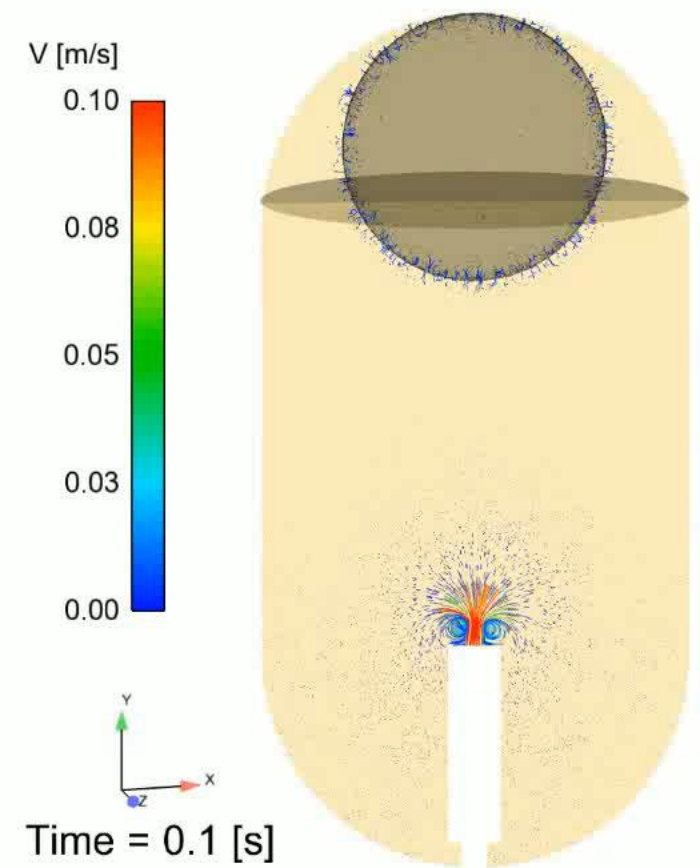
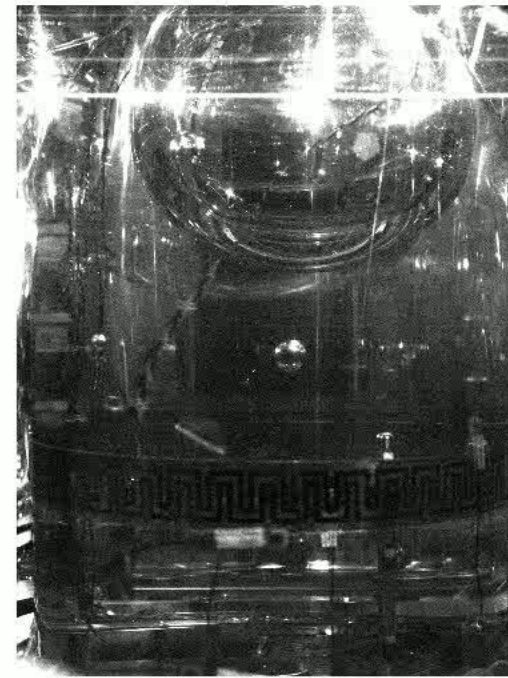


LES

Simulations of the temperature and flow fields using the LES CFD model

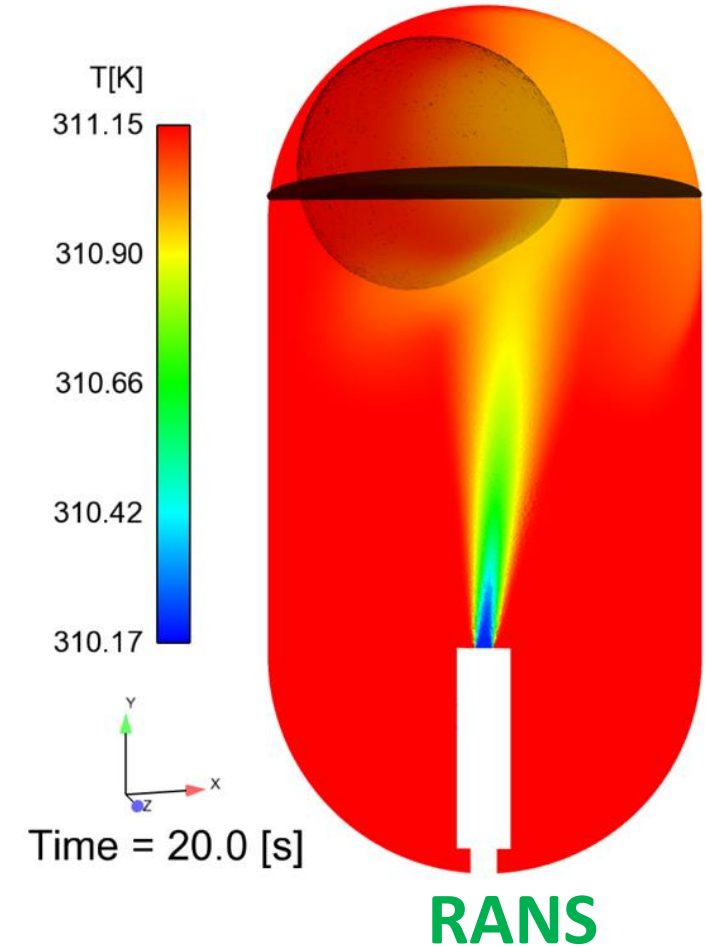
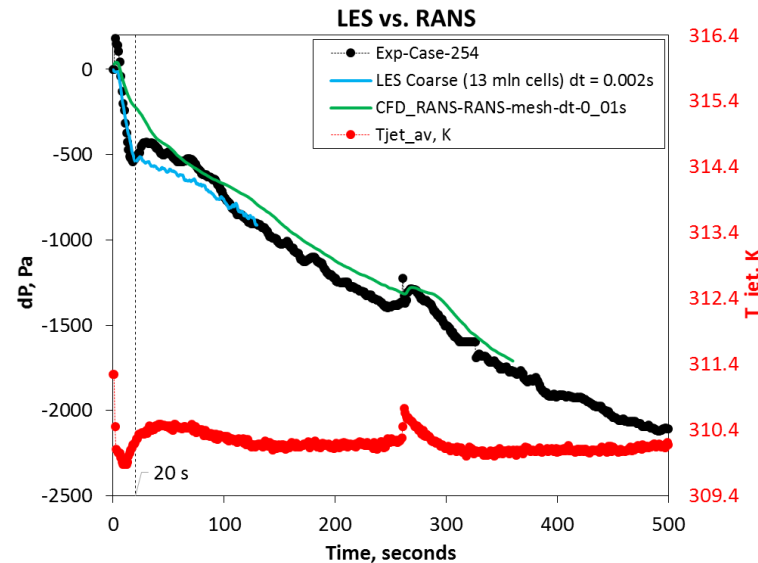
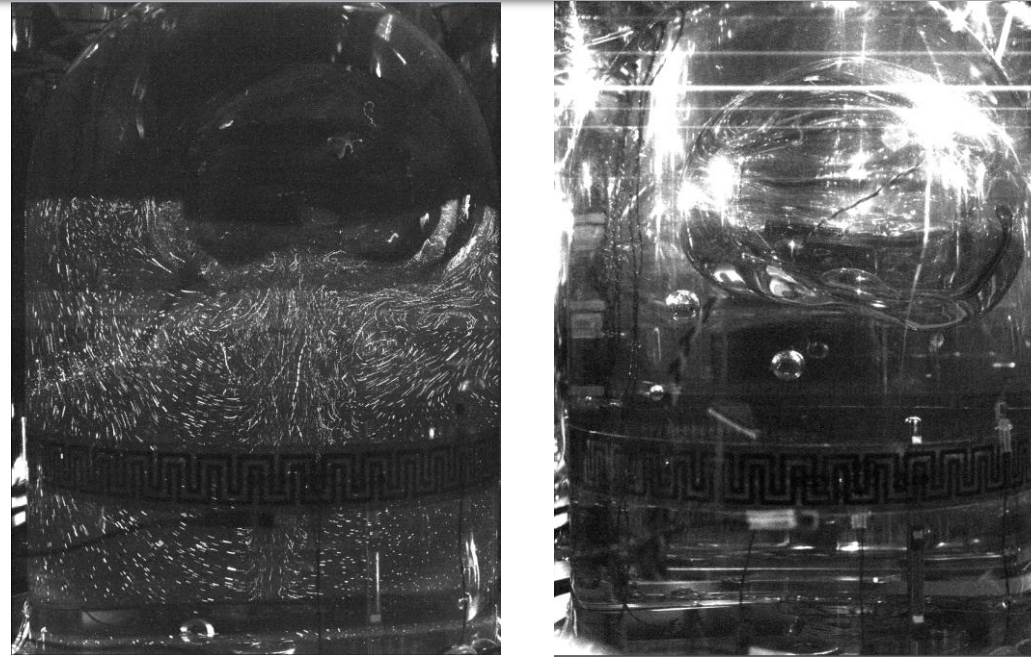
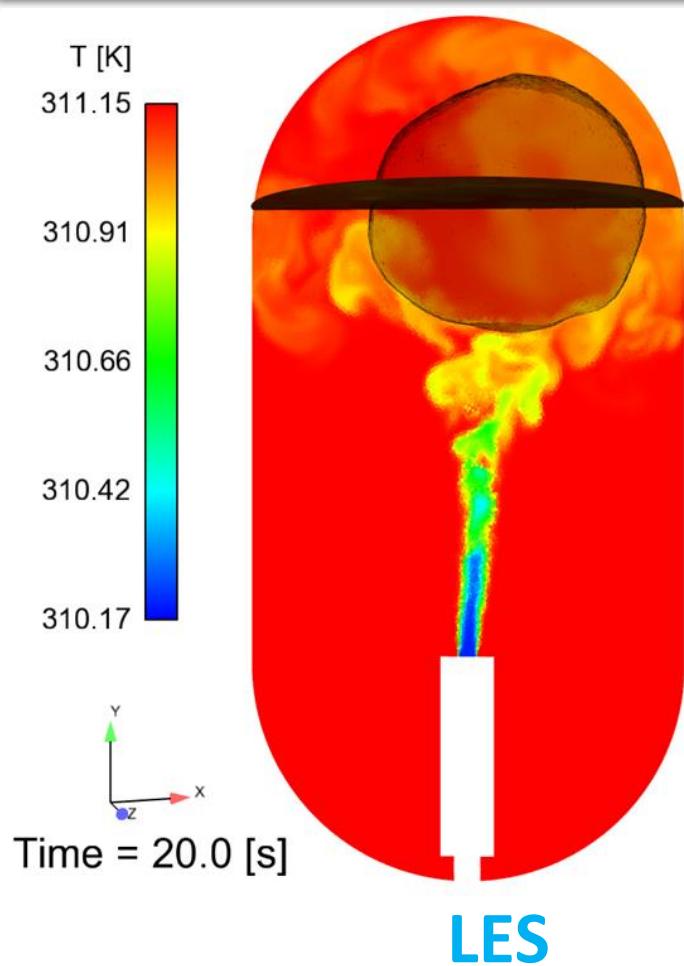


LES - Temperatures

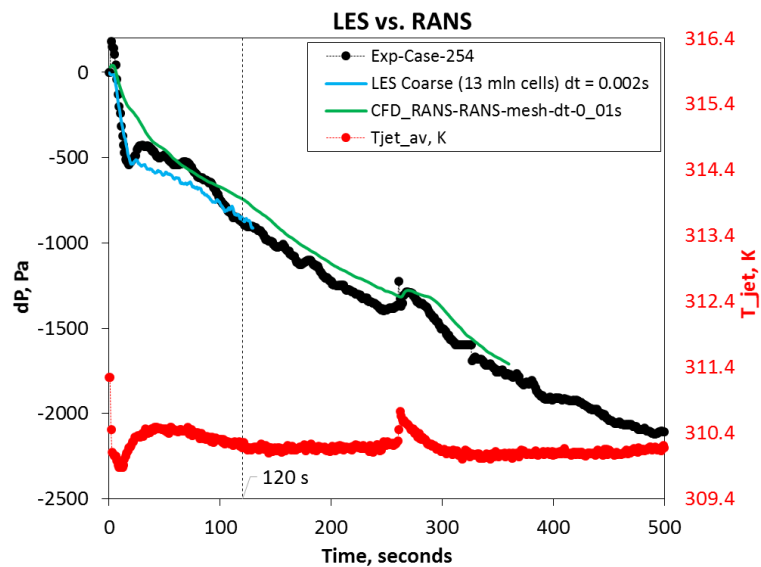
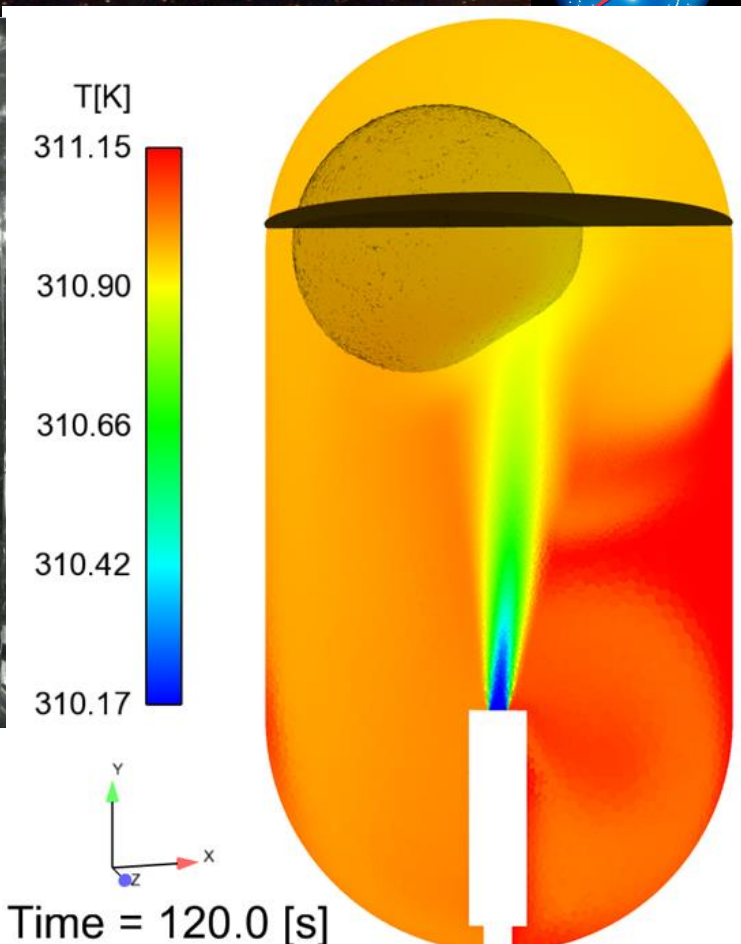
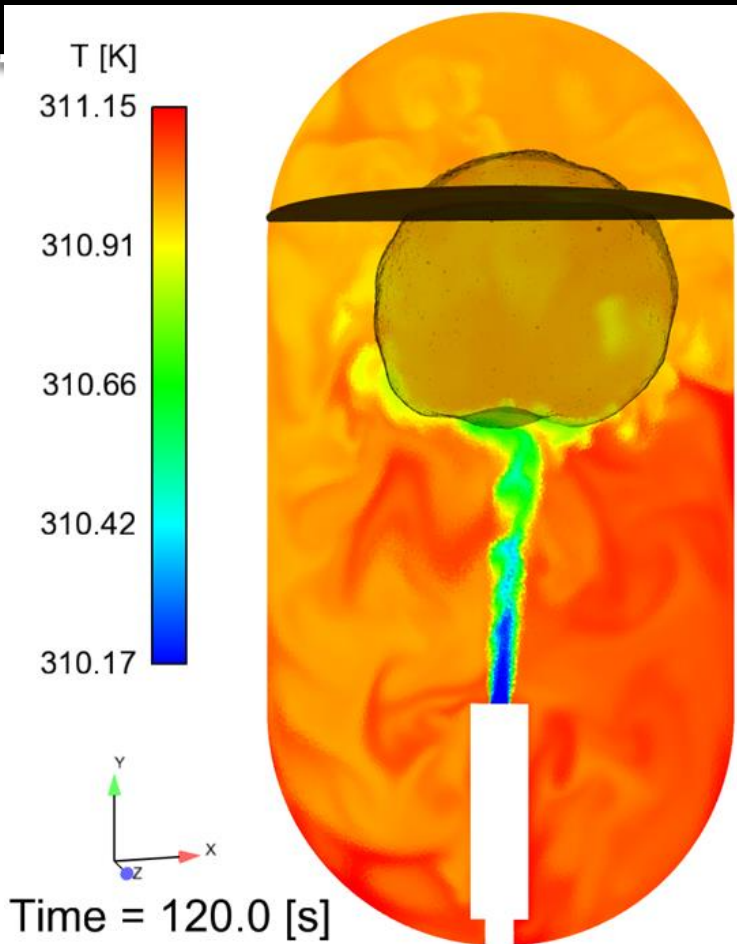


LES -Flow

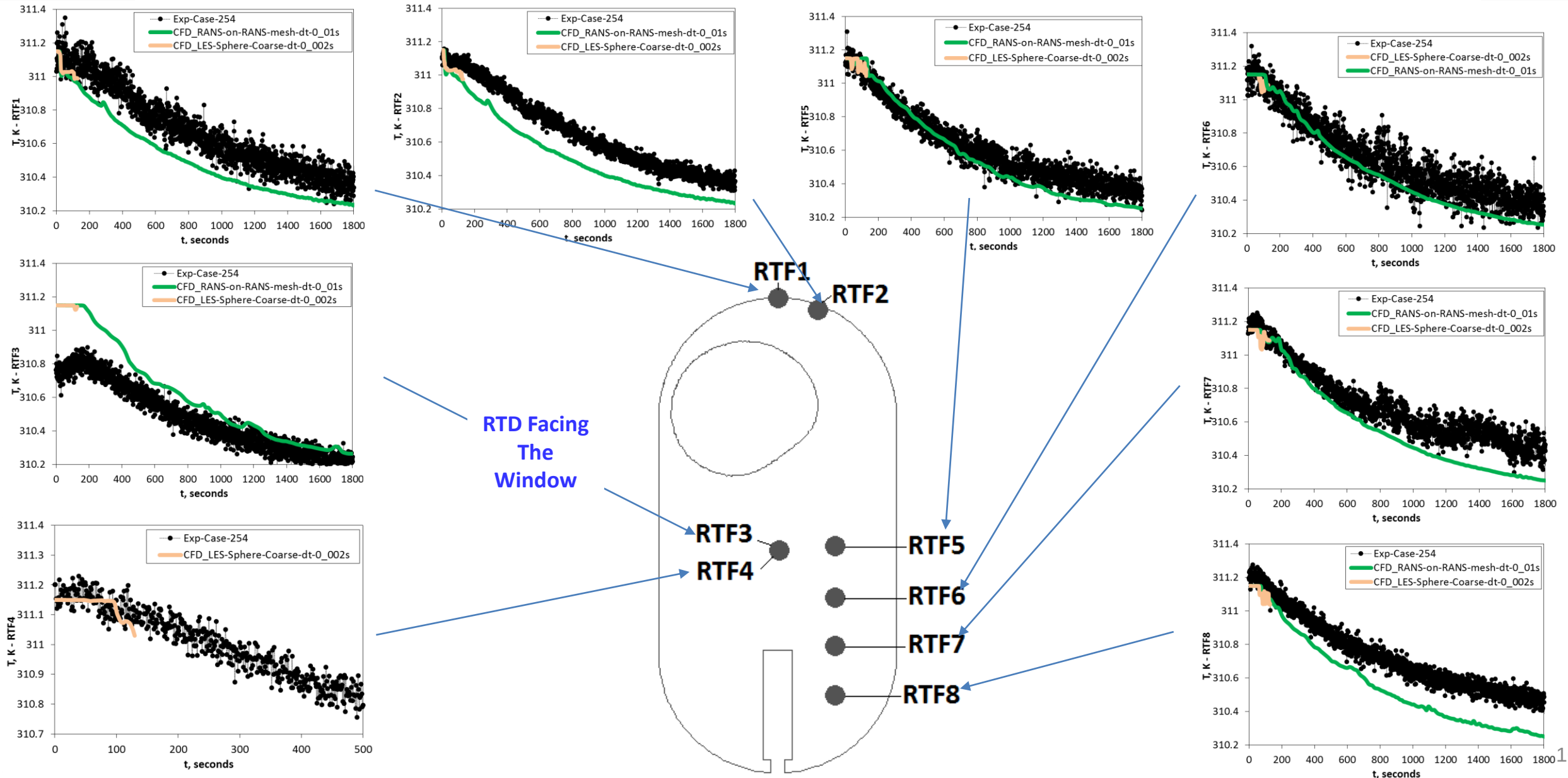
ZBOT Case 254: 90.62% fill level, 10 cm/s jet speed, T0-1 jet Temp



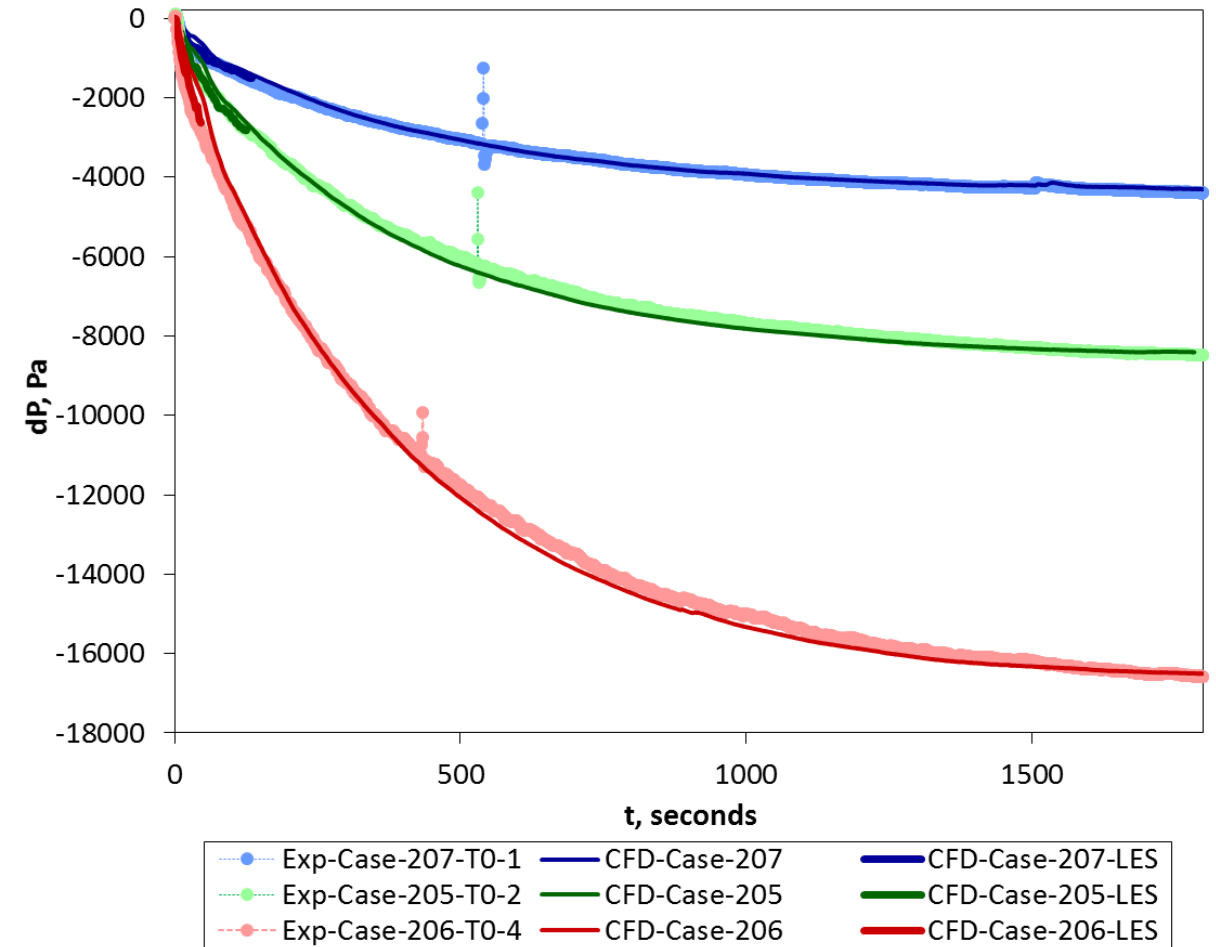
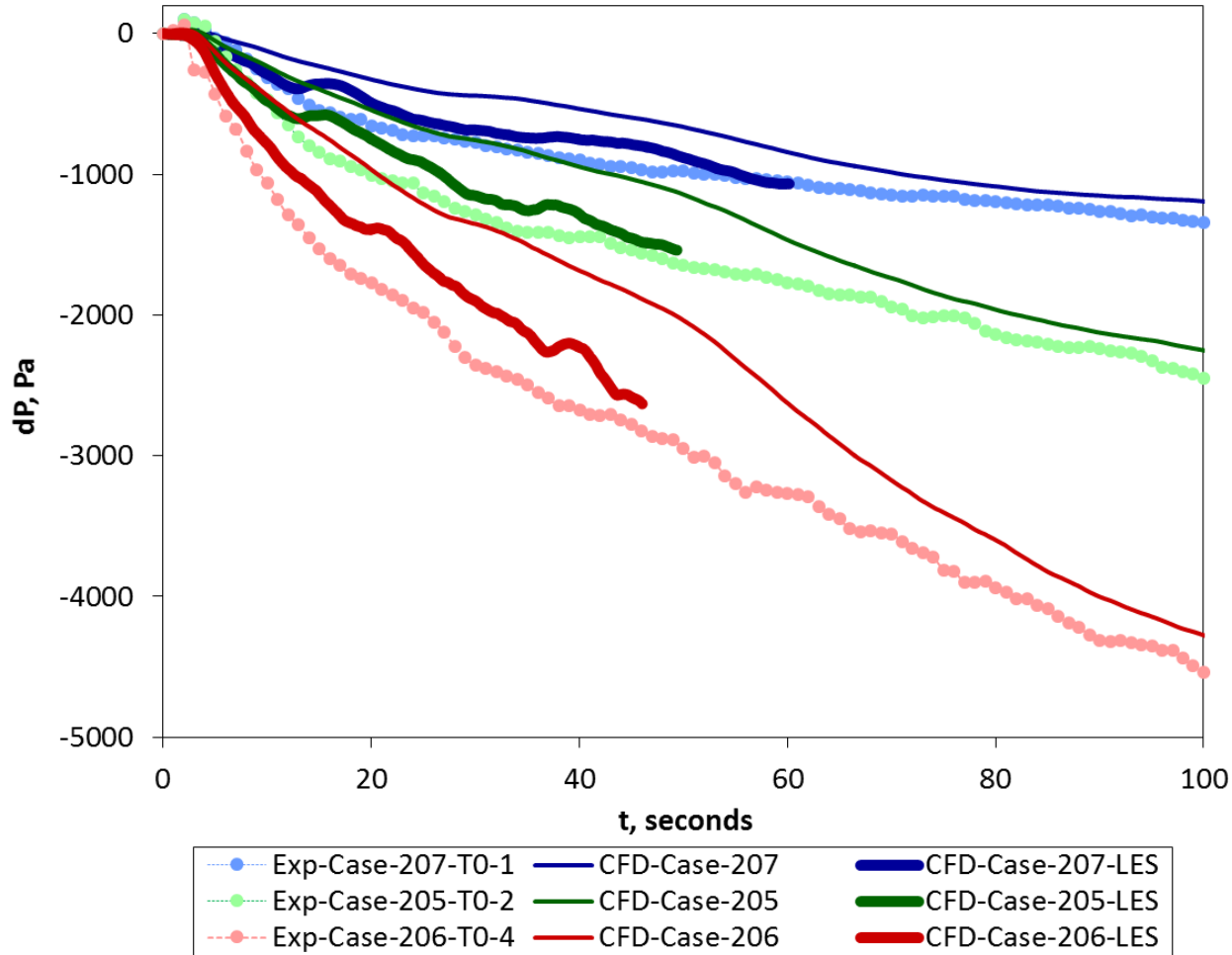
ZBOT Case 254: 90.62% fill level, 10 cm/s jet speed, T0-1 jet Temp



ZBOT Case 254: 90.62% fill level, 10 cm/s jet speed, T0-1 jet Temp



ZBOT Cases 207, 205 and 206 – LES vs. RANS: Tank Pressure





Pool Boiling/ Cavitation during Microgravity Self-Pressurization & Subcooled Jet Mixing Pressure Control

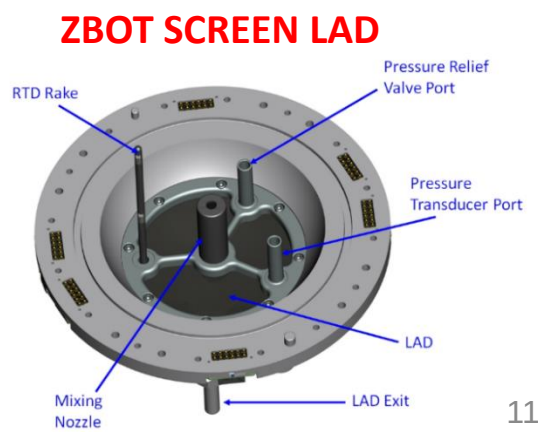
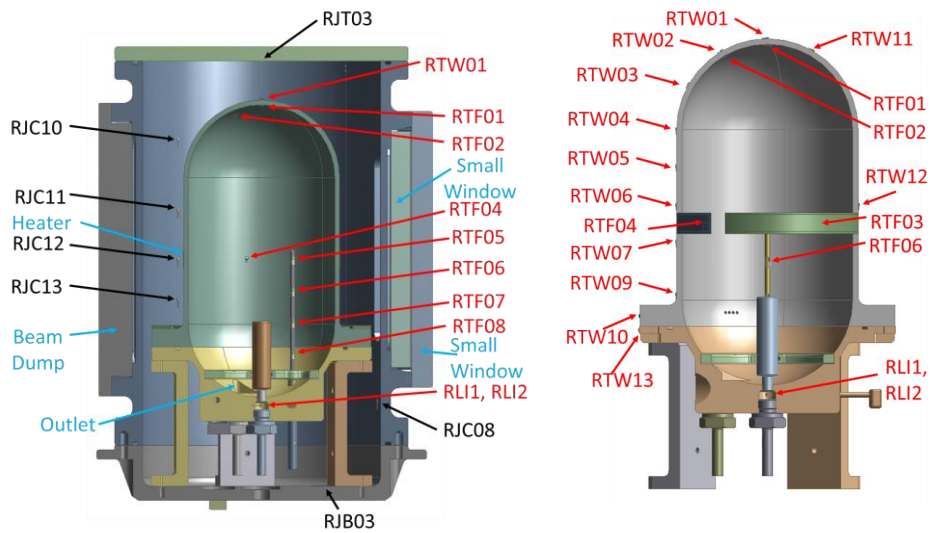
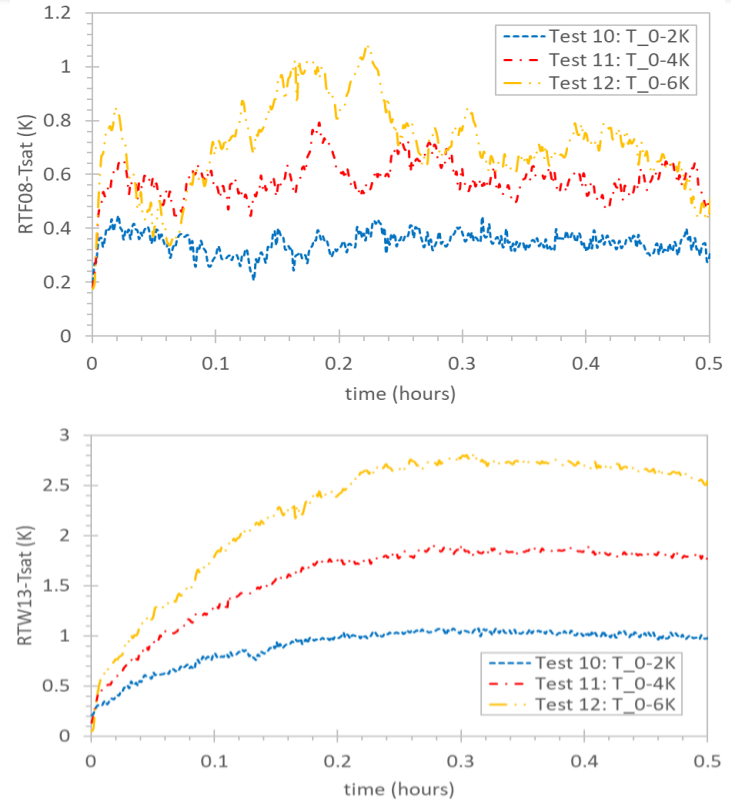
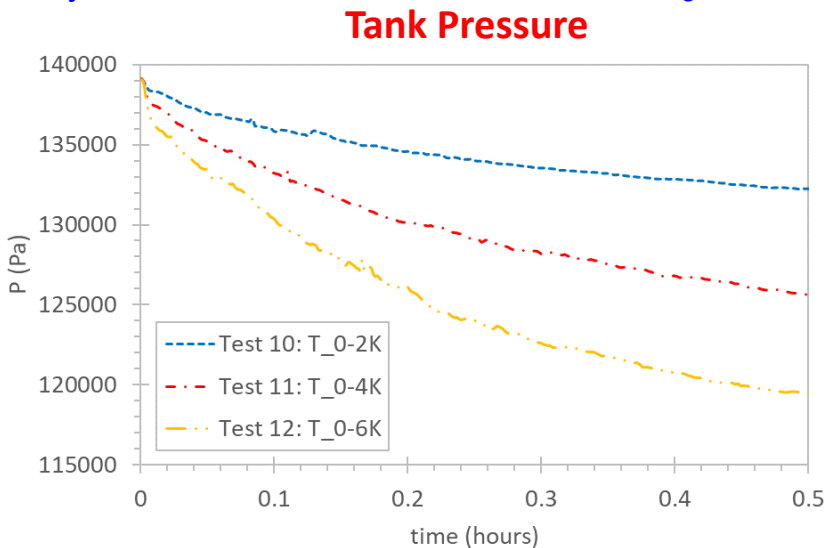
ZBOT Results - Microgravity Boiling at the LAD during Subcooled Jet Mixing Pressure Control



(#11) T_0 -4 K 6 cm/s SC Jet
30 min 1 f/2s



$T_{vj} = T_T$
 $V_{jet} = 6 \text{ cm/s}$
 $FL = 70\%$
 $T_0 = 38 \text{ C}$



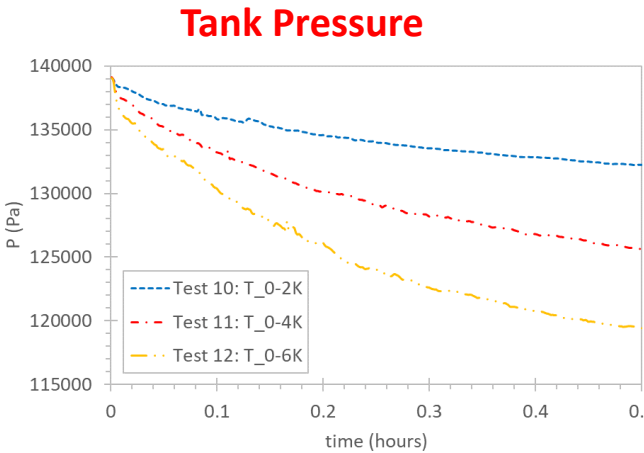
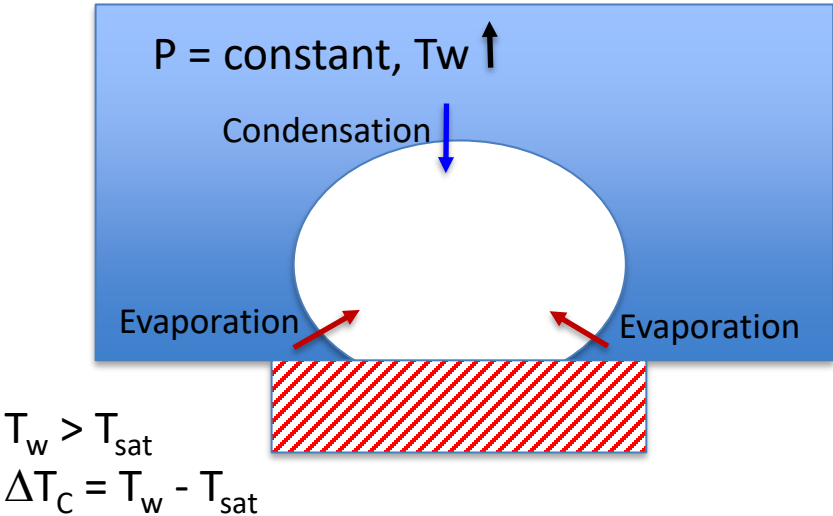
ZBOT Results – Boiling or Cavitation ???

CE Brennen, *Cavitation and Bubble Dynamics*, Oxford University Press 1995



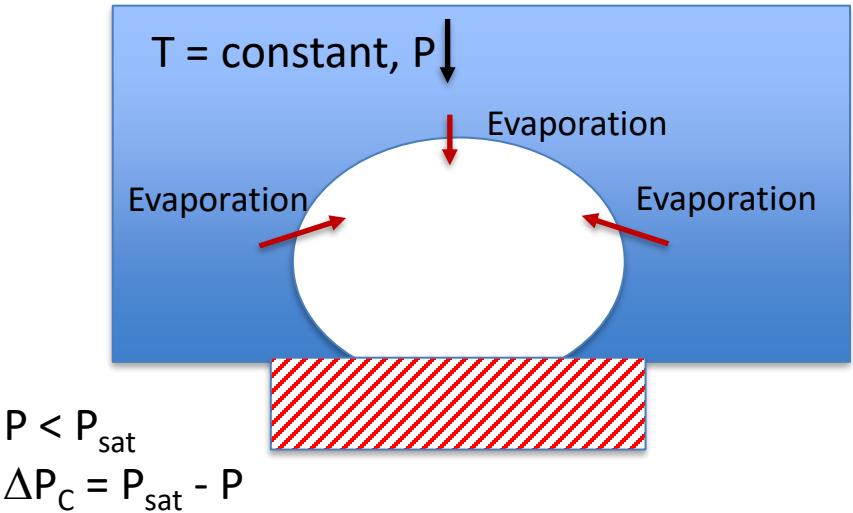
Boiling:

A liquid at **constant pressure** may be subjected to a temperature, T_w , in excess of the normal saturation temperature, T_{sat} . The value of $\Delta T = T_w - T_{sat}$ is the superheat, and the point at which vapor is formed, ΔT_c , is called the **critical superheat**. *The process of rupturing a liquid by increasing the temperature at roughly constant pressure is often called boiling.*



Cavitation:

A liquid at **constant temperature** could be subjected to a decreasing pressure, p , which falls below the saturated vapor pressure, p_{sat} . The value of $\Delta p = (p_{sat} - p)$ is called the tension,, and the magnitude at which rupture occurs is the tensile strength of the liquid, Δp_c . *The process of rupturing a liquid by decrease in pressure at roughly constant liquid temperature is often called cavitation.*



Critical Rupture Pressure

Test #	$T_{jet} - T_{tank}$	$\Delta P_c = P_{sat} - P$
10	-2	4,000
11	-4	7,000
12	-6	10,000

Fluid Physics Implications of ZBOT findings for CFM of Propellant Tanks



Self-Pressurization:

- ❖ For a tank designed and operating under low heat loads, Self-Press in μG proceeds under near thermodynamic equilibrium conditions → Can be modeled by both thermo-based and Kinetic-based interfacial mass transfer models.
- ❖ μG Self-Press follows the same behavior and trend as 1G but at lower rates and magnitudes → Ground testing provides a conservative estimate for flight pressurization rate
- ❖ Due to mitigated convection, 0G thermal stratification, and lower heat fluxes needed to reach $\Delta T_{\text{incipient}}$, boiling in μG may be prevalent producing pressure spikes → These localized boiling will be presumably less impactful for a large tank

Jet-Mixing:

- ❖ Behavior and interaction with the ullage in μG is non-intuitive and quite different at any jet velocity compared to 1G.
- ❖ At high jet flow rates, the ullage will deform & maneuver to avoid/accommodate the jet → The envisioned ullage splitting may not occur due to lack of perfect alignment.
- ❖ At low flow rates, the ullage will move against the jet flow direction → Forced jet flow with a minor tilt may be used to move/reposition the ullage and control the ullage location.
- ❖ Turbulence effects dominate Jet – Ullage Interaction → LES are necessary to capture jet behavior and correct ullage deformation with fidelity

Subcooled Jet Mixing:

- ❖ Subcooled jet mixing cycle can provide rapid and large ullage pressure drops as cold jet surrounds the ullage and interfacial condensation is strongly promoted → Effective means of pressure reduction
- ❖ Unfortunately it can also promote pool cavitation at localized hot spots not reached effectively by the jet and may cause →
 - Massive phase change at very small ΔP_c - if good nucleation spots are available such as on LAD/screens
 - Since phase change occurs at both sides of LADs/Screen it may be lead to vapor ingestion by lines feeding the engine
- ❖ Both jet mixing & spray bar pressure control design have to be carefully assessed for their ability to provide uniform cooling in large tanks
- ❖ Requirement may be necessary to prevent internal boiling/cavitation & LAD breakup → such as provide internal LAD cooling

Fluid Physics Implications of ZBOT findings for CFM of Propellant Tanks



Impact of Sudden & Background Acceleration:

- ❖ Background residual low frequency gravity is impactful as tank is self-pressurizing → its magnitude and direction must be monitored especially in a large tank (MAMS)
- ❖ Tank fluid dynamics and heat transfer are not affected by high frequency accelerations such as those imparted during coasting operations
- ❖ Tank fluid dynamics and heat transfer are affected by moderate frequency acceleration/short duration accelerations due to thrust or re-boost → these can cause considerable pressure spikes and fluid motion in a stratified tank (SAMS)



Non-Condensable Gas Pressurant Effects

Liquid Propellant Thermal Conditioning System Test - Lockheed 1972

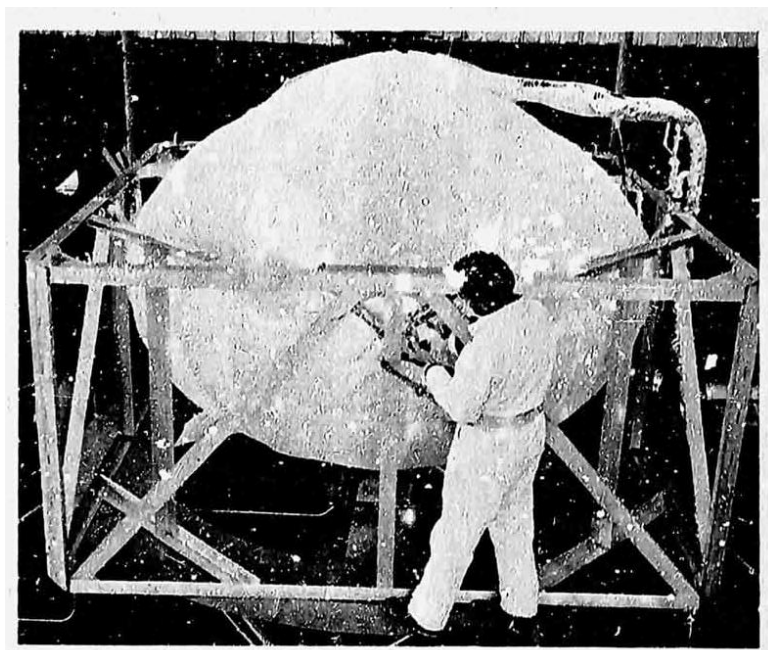
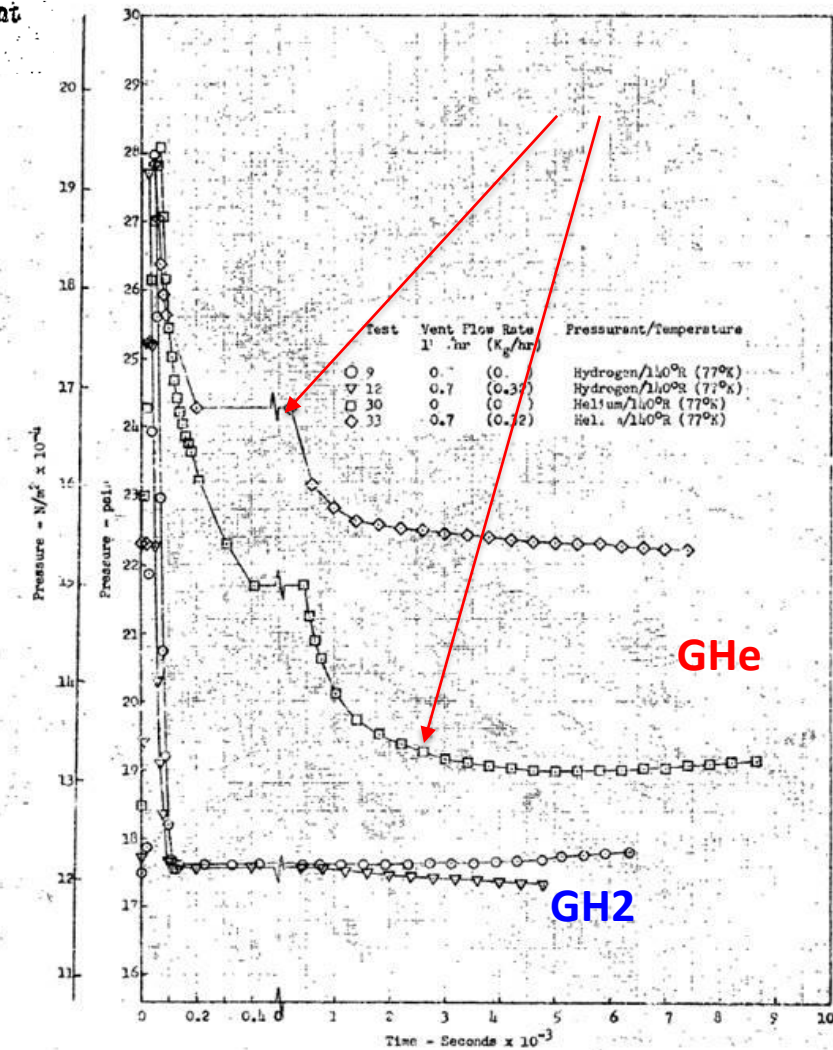
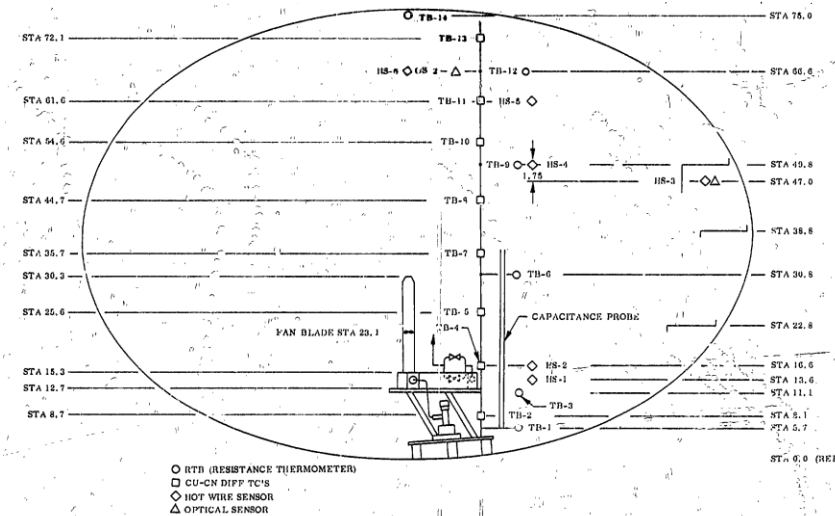
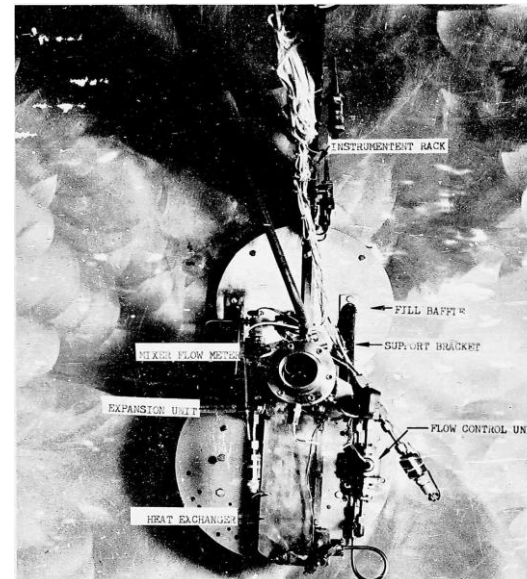


Figure 58 Comparative Effect of Vent Rate And Pressurant at 5 Percent Ullage - 110 Inch (2.8 m) Tank - Bottom Mount



- LH2 Pressurized with like (GH2) and NCG (GHe)
- 110 in – 2.8 m Tank
- Depressurization by mixing alone using bottom- and side-mount nozzle/pump and by mixing and cooling using a TVS system
- Results for 95% FL – Bottom Mount
- Mixer flow rate 5.3 cfm – 150 L/min
- Effect of Mixing, Cooling, NCG



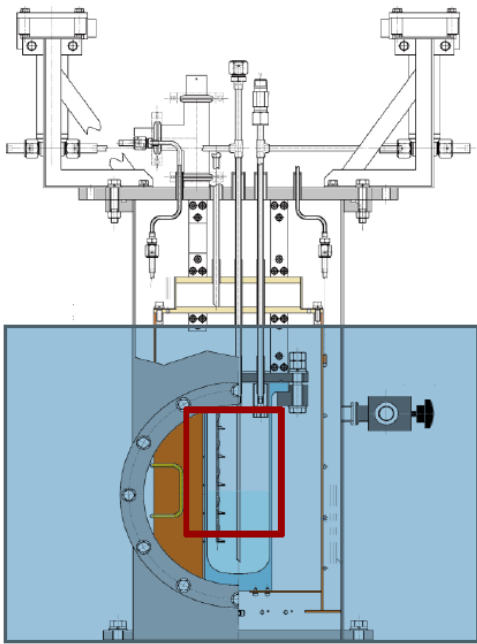
Effect of Noncondensable pressurant on pressure drop in a LH2 tank during jet mixing with and without TVS cooling [Bullard, 1972]

1G LN2 Tank Pressurized Slosh Experiments (University of Tokyo) - 2016



- Cylindrical polycarbonate vessel (ID = 0.105 m)
- Filled with LN2 pressurized with GN2 or GHe
- Periodical sloshing caused by lateral external sinusoidal oscillation: 2.45 Hz – 10 mmp-p

Fluids	Fluid Conditions				Oscillating Conditions		
	Initial Press.	Liquid Level	Initial Temp.		Freq.	Amp.	Time
	MPaG	mm	Gas	Liquid	Hz	mmp-p	s
LN2-GN2	0.2998	151.3	91.5	79.6	2.45	10	60
LN2-GHe	0.3009	150.2	84.7	79.4	2.45	10	60



Constant Amplitude

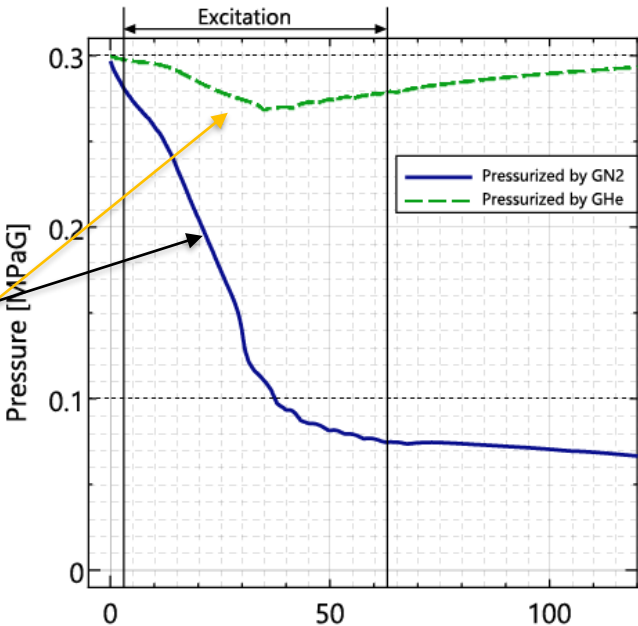
Suppression of condensation & pressure drop in a LN2 tank during a slosh experiment when the tank is pressurized with **GHe** as compared to pressurization by **GN2**. (Haba et al, Space Prop. 2016).

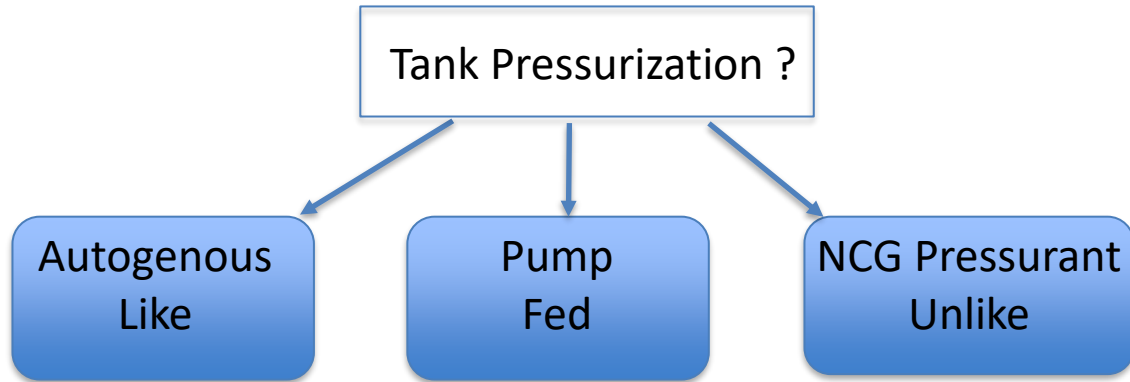


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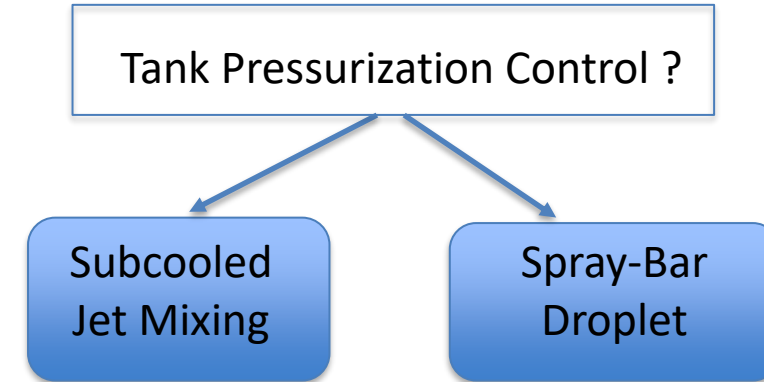


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- Tank pressurization with a gaseous pressurant is used to extract liquid for feeding the engine or during propellant transfer and coasting operations.
- Noncondensable gas pressurization is more robust than pump fed operations because it is not as susceptible to mechanical failure.
- It also may be preferred over autogeneous pressurization which is more operationally complex.



- Subcooled Jet mixing relies on condensation to control tank pressure .
- Spray-Bar Droplet injection depends largely on droplet evaporation to reduce tank pressure
- If Evaporation not effected by NCG as much as Condensation Spray-Bar Droplet mechanism may be the preferred choice



- Great Progress has been accomplished in Propellant Tank CFM especially regarding Self-Pressurization and Pressure Control through:
 - ❖ 1G & Microgravity Experiments
 - ❖ Model Development & Validation
- Future work should concentrate on improving our understanding of:
 - ❖ Interfacial Turbulence Effects
 - ❖ Noncondensable Gas Effects
 - ❖ Microgravity Boiling Regimes
 - ❖ Depressurization Cavitation



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