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October 25-28, 2017

Zero-Boil-Off Tank (ZBOT) Experiment – Ground-Based Validation of Self-Pressurization & Pressure Control Two-Phase CFD Model

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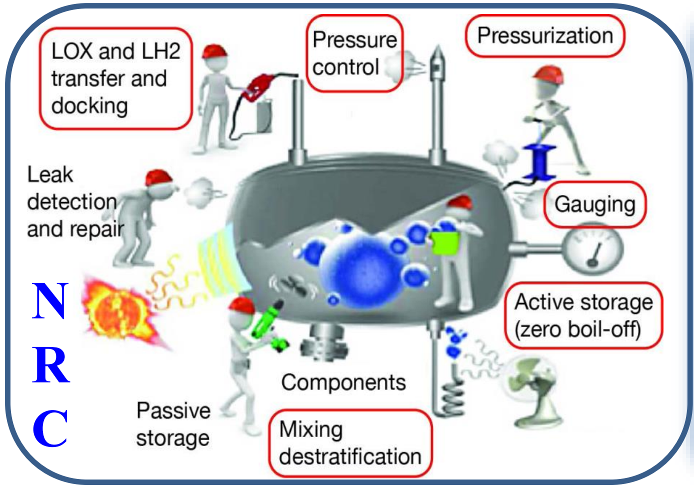
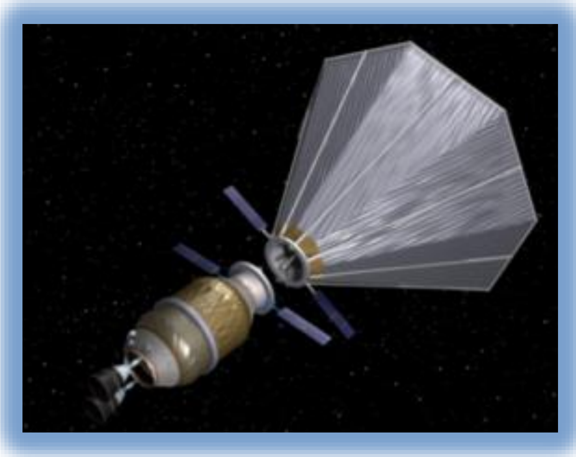
October 28, 2017

Zero Boil-Off Tank (ZBOT) Experiment

- Cryogenic Fluid Management of propellant storage tanks is in the critical path of most envisioned NASA exploration mission including mission to Mars
- The Zero Boil Off Tank (ZBOT) experiment provides A small-scale *simulant*-fluid investigation of storage tank pressurization and pressure control in the Microgravity Science Glovebox (MSG) unit aboard the ISS. Its objectives are to:
  - Elucidate the roles of the various interacting transport and phase change phenomena that impact tank pressurization and pressure control in microgravity to form a scientific foundation for storage tank engineering.
  - Obtain microgravity data for tank stratification, pressurization, mixing, destratification, and pressure control time constants during storage.
  - Develop a *state-of-the-art* CFD two-phase model for storage tank pressurization & pressure control.
  - Validate and Verify the zonal- and CFD-based tank models using the microgravity data. Use the model and correlations to optimize and scale-up future storage tank design




Cryogenic Propellant Depots (credit: ULA concept)


In Situ Resource Utilization (ISRU) Lox/CH4 Spacecraft Propulsion


Large Propulsion Stages

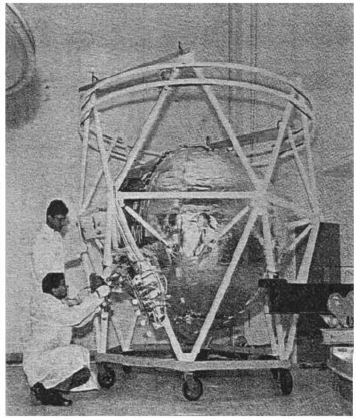
Notional Pathway to Mature Understanding Of CFM Fluid Physics and Validated Computational Models

- Natural Convection
- Forced Mixing
- Evaporation/Condensation
- Microg Superheats/Nucleate Boiling
- Droplet Breakup & Transport
- Droplet Phase Change
- Microgravity Two-Phase Flow & Heat Transfer Regimes/Transitions
- Interfacial Turbulence Effects
- Vapor-Side Turbulent Transport
- Non-Condensable Gas Transport
- Double Diffusive Barriers
- Marangoni Convection
- Interfacial Mass Transfer Kinetics
- Capillary Flow & Free Surface Dynamics
- Contact Angle Dynamics & Thin Film Evaporation
- Sloshing
- Phase Control/Positioning

Experimentation

Modeling/Analysis

1-g Data

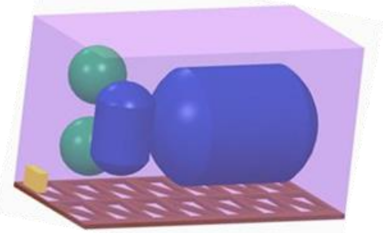


K-Site, MHTB

μg-Fundamentals (Simulant Fluids)

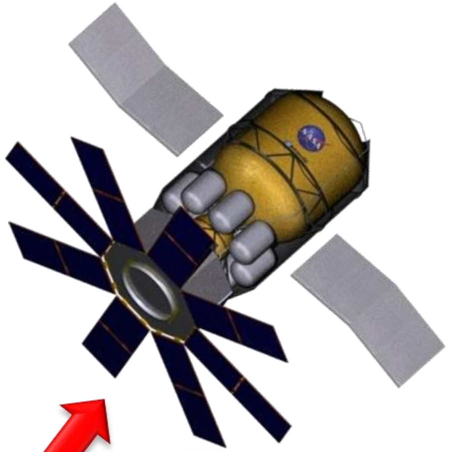
ZBOT, TPCE

μg-Subscale Experiments (Cryogens)



RMM3, Other Notional ISS JEM Cryo Experiments

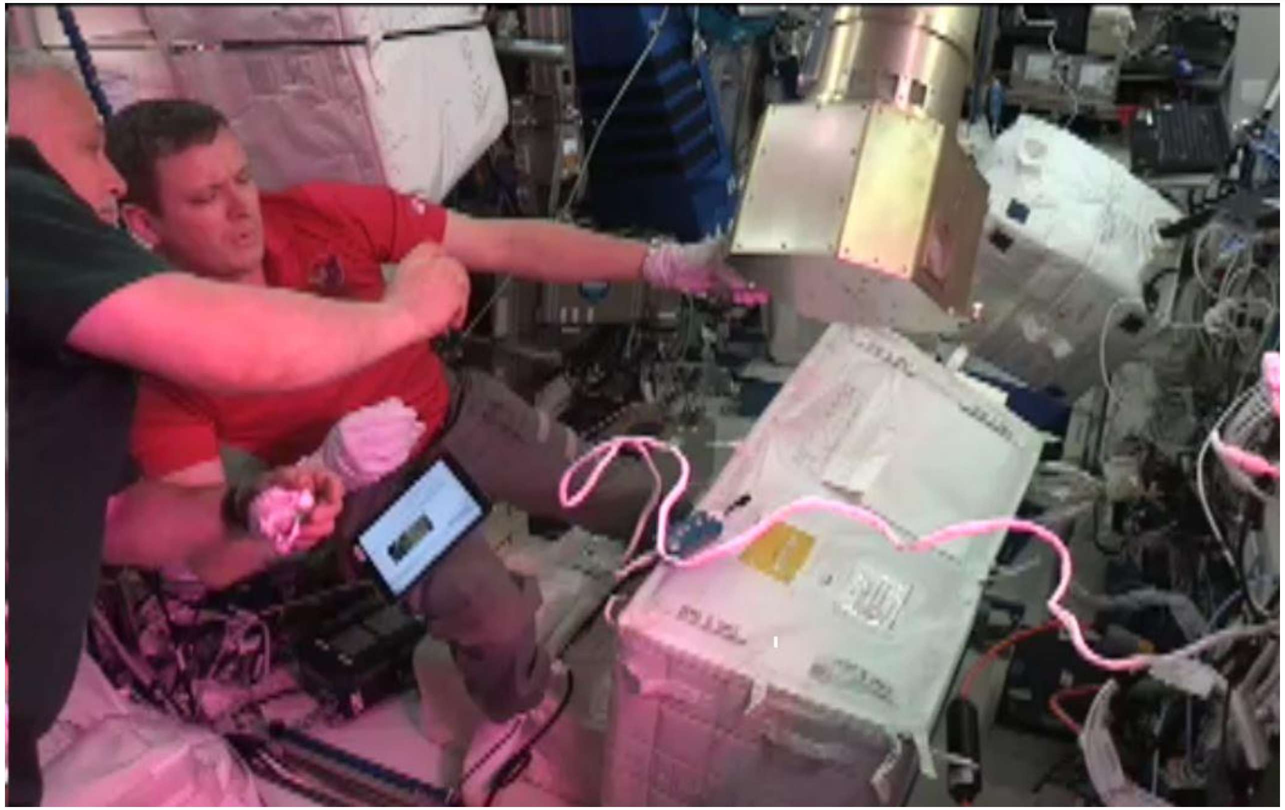
Cryo Demonstrations

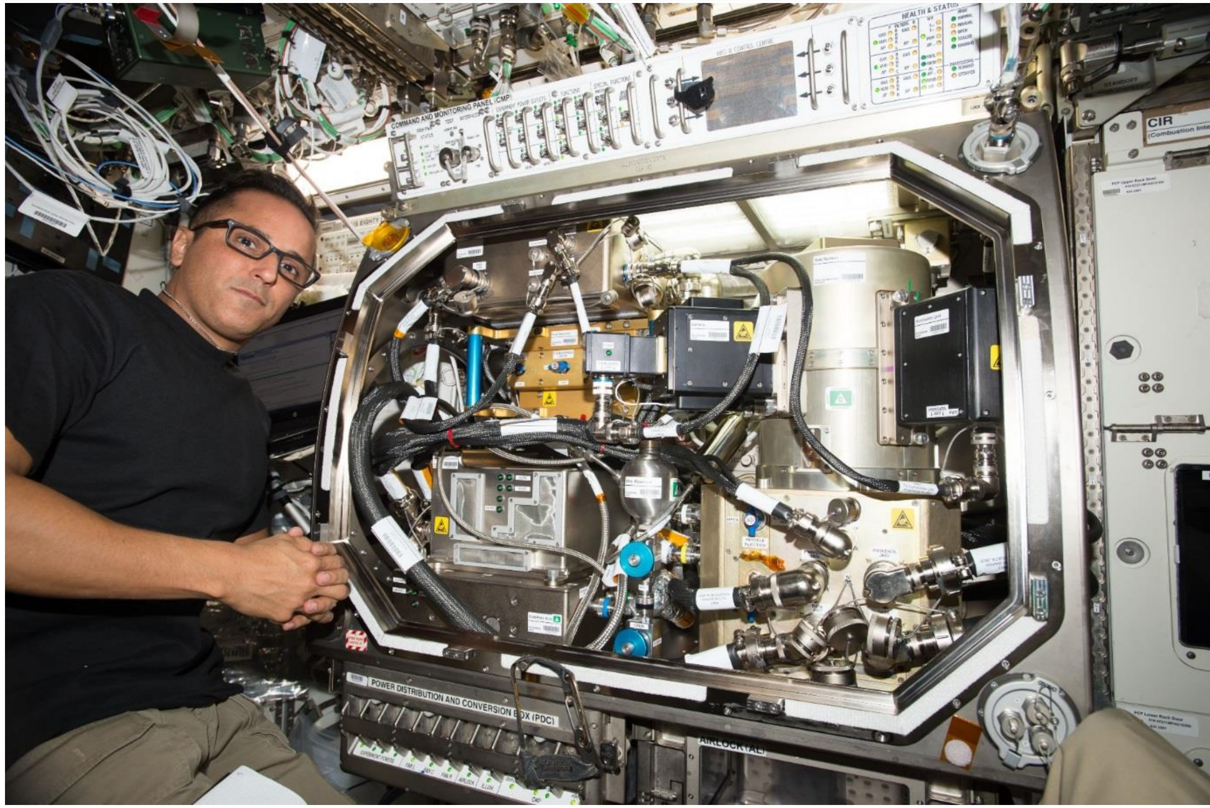


SOA Models

- ➢ **Multinode Models: GFSSP, Sinda/Fluint**
- ➢ **CFD Models: Ansys/Fluent, Flow3D**

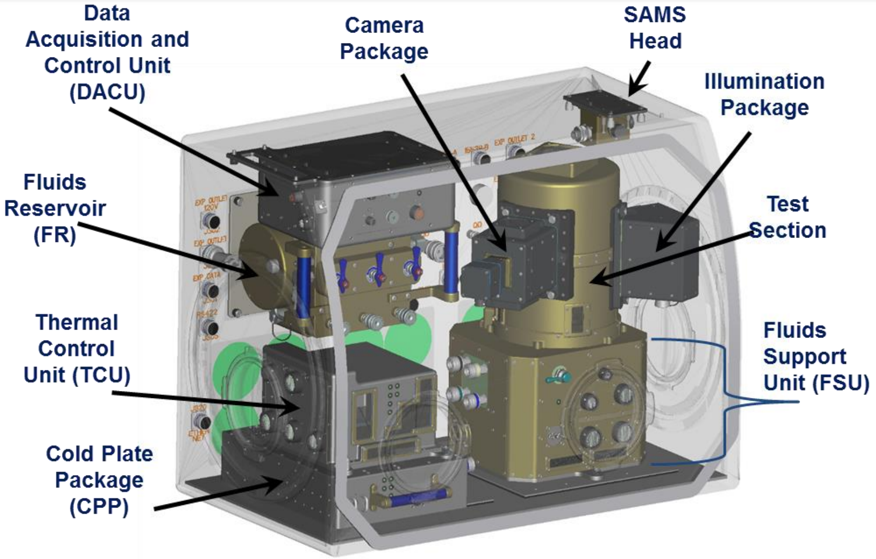
ZBOT Hardware in MSG Aboard ISS



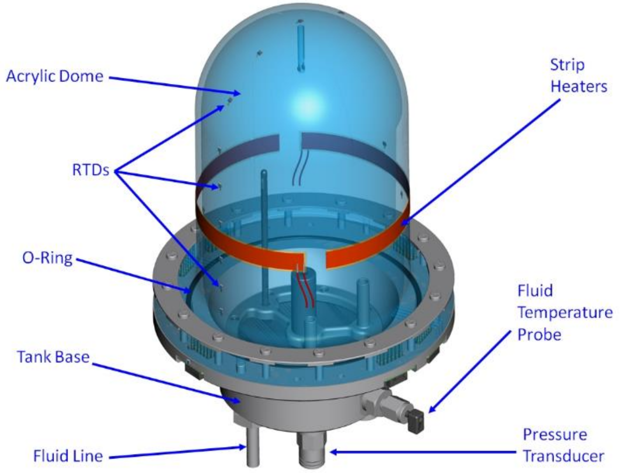


- ➢ Experiment was installed by Astronaut Joe Acaba on September 19 & 20th in the MSG and powered up.
- ➢ System thermal & fluid characterization started on September 24th
- ➢ Actual Test runs began on Oct 1st
- ➢ Currently the 70% test runs are being conducted and near completion
- ➢ Data and images are being downloaded continuously

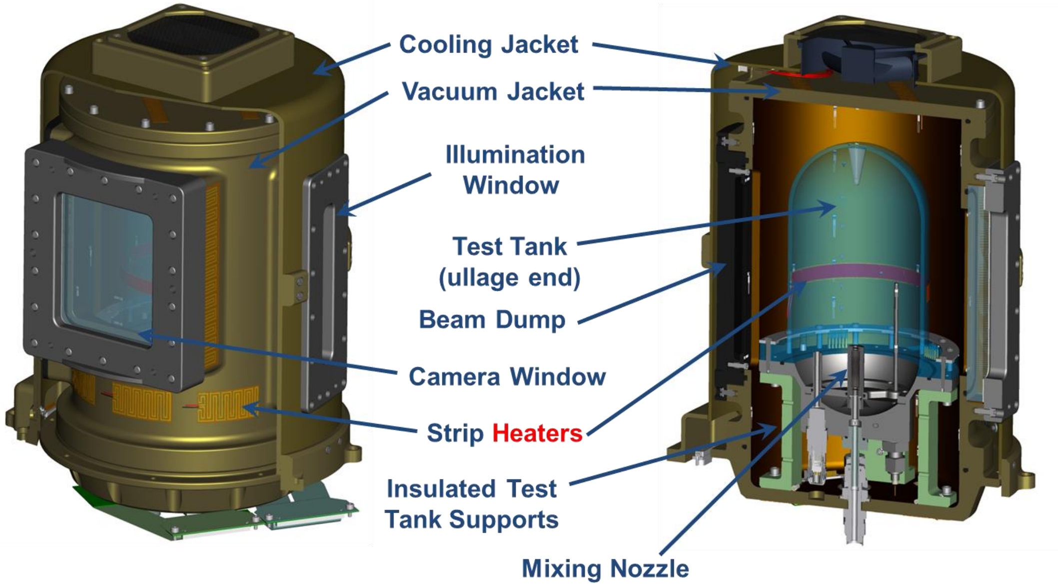
ZBOT Hardware Components



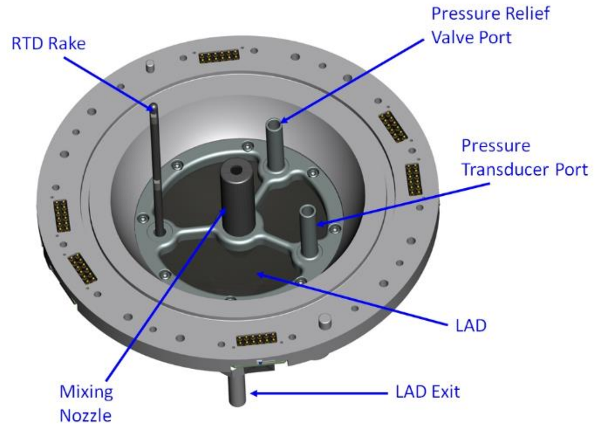
ZBOT Hardware Components in MSG



Acrylic Test Tank Dome

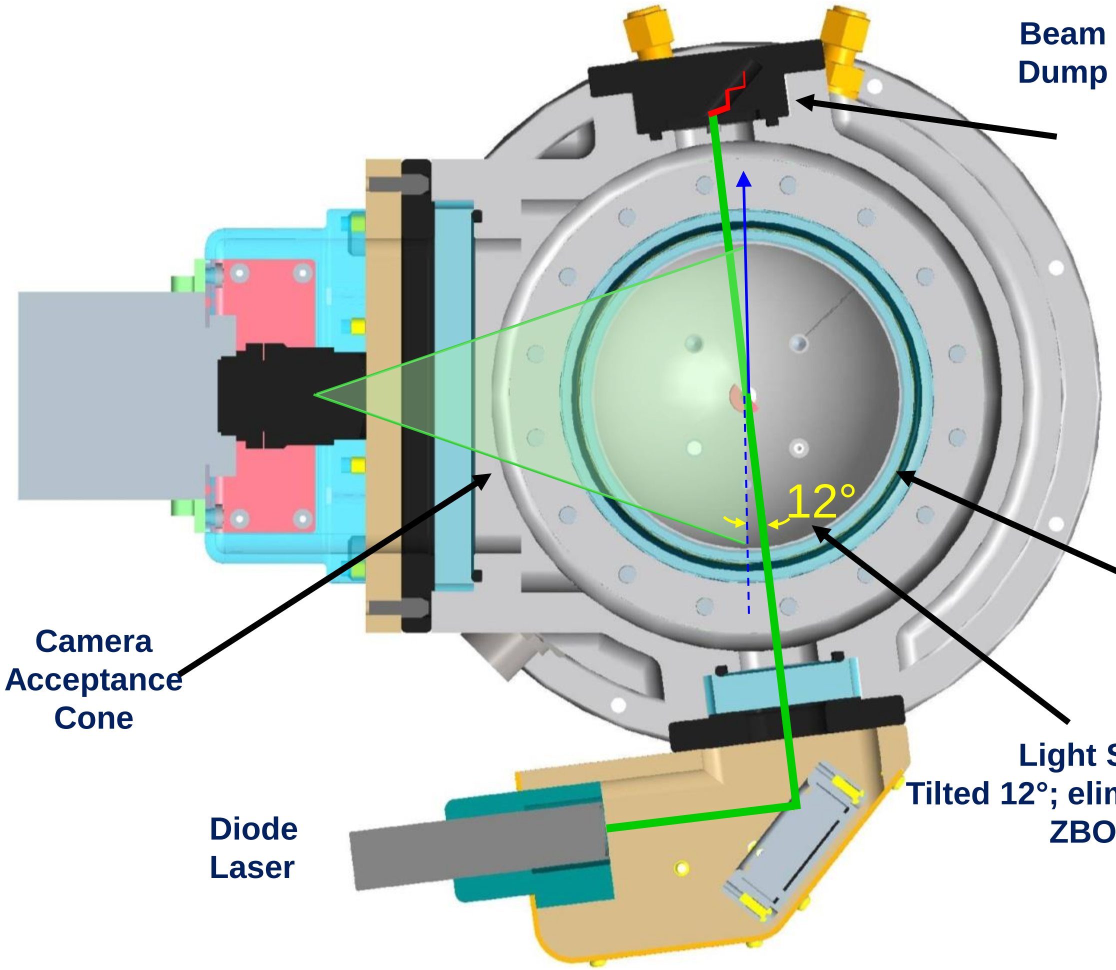


ZBOT Test Tank inside the Vacuum Jacket



Stainless Steel Test Tank Base, Nozzle & Screen LAD

ZBOT Camera & Illumination Package for Image Capture & PIV



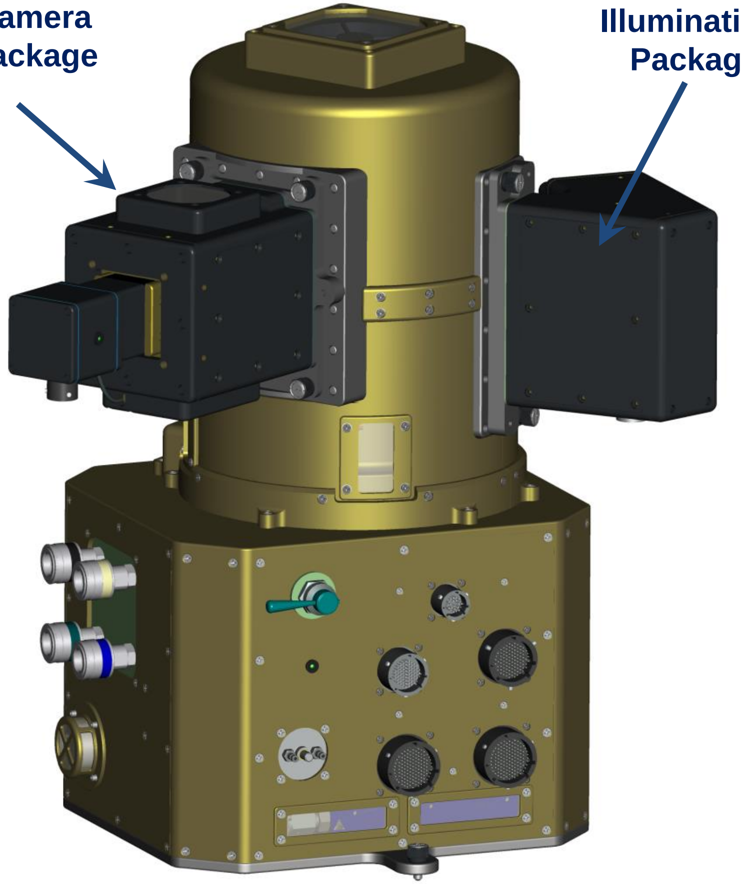
Beam
Dump

Tank

Camera
Acceptance
Cone

Light Sheet
Tilted 12°; eliminate tilt for
ZBOT-2

Diode
Laser



Camera
Package

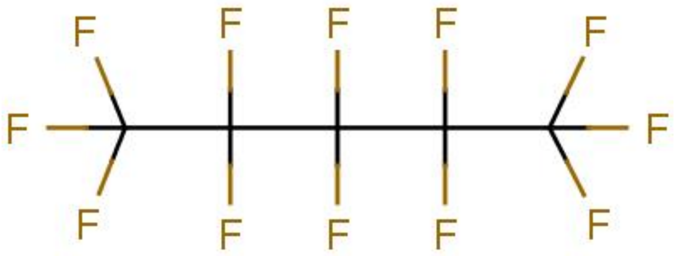
Illumination
Package

ZBOT Tank Pressurization & Mixing Cooling Test Matrix

- 68 pressurization, jet mixing, and destratification tests will be performed first at 3 fill levels with and without Particle Imaging Velocimetery (PIV)
- 30 Tests will be repeated with particles injected & PIV performed as Tech Validation

Perfluoro-n-Pentane

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



- Refrigerant/Cleaning fluid
- High purity (99.7% straight-chained n-isomer)
- Boiling Point = 29°C @ 1 atm
- Vapor Pressure = 12.5 psia @ 25°C

Benefits

- Boils Near Room Temperature
- Near zero contact angle with test tank
- Tox 0 – Approved by JSC toxicology and MSFC ECLSS groups as safe for use within International Space Station

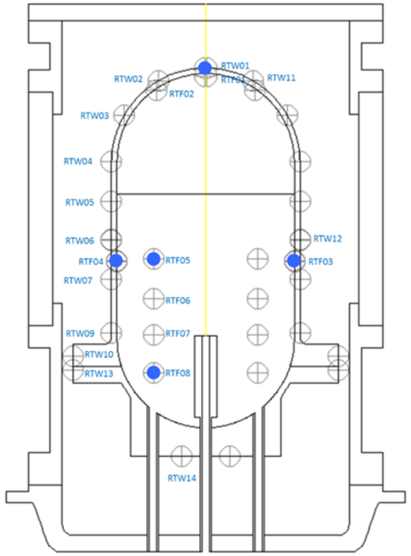
Type of Test	Method & Mode
Pressurization	Heater Strip
	Vacuum Jacket Heating
	Heater and Vacuum Jacket
Mixing Only	Uniform Temperature
	After Self-Pressurization
Subcooled Mixing	Uniform Temperature
	After Self-Pressurization

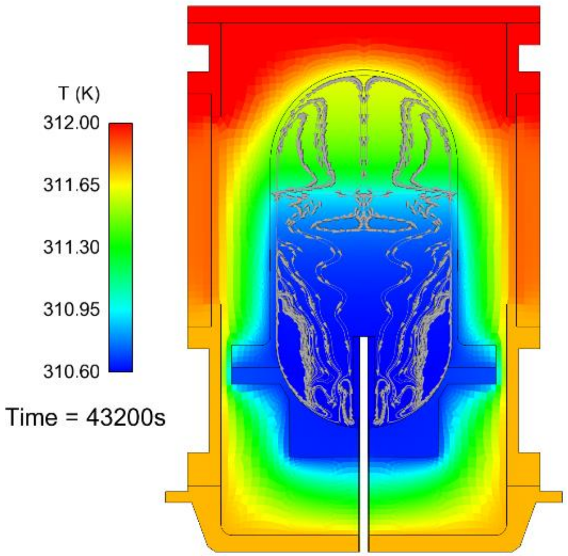
Input Variables (Tolerances)
Heater Power (w/ in 5 mW RMS)
Vacuum Jacket Offset (+/- 0.2°C)
Fill Level (70% +/- 3%, 80% +/- 3%, 90% -3%)
Jet Temperature (+/- 0.25°C)
Jet Velocity/Flow rate (10% of reading)

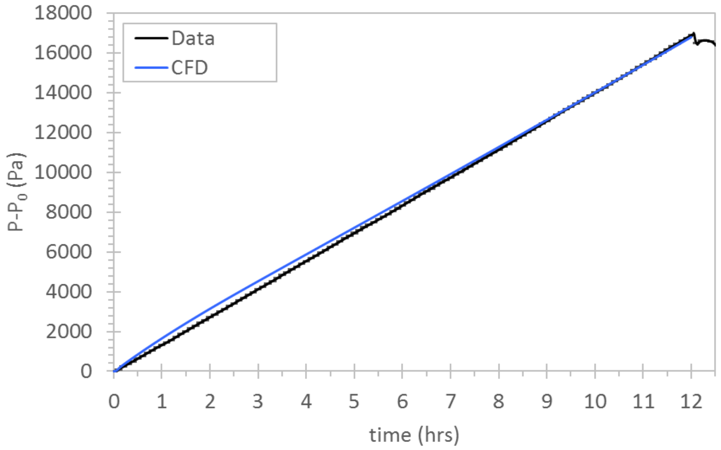
Outputs as Time Evolution
Pressure
Fluid Temperature (6 locations)
Wall Temperature (17 locations)
Jacket Temperature (21 locations)
Jet Penetration Depth
DPIV Velocity/Flow Structures

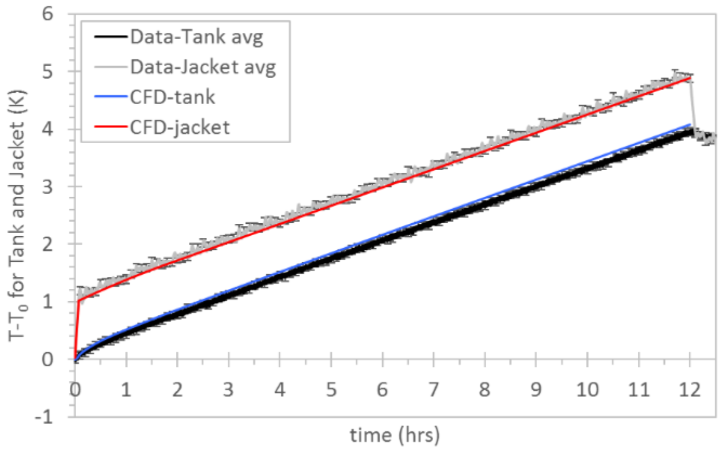
Ground Based Model Validation Experiment in Flight Hardware: 1G Self-Pressurization - Vacuum Jacket Heating

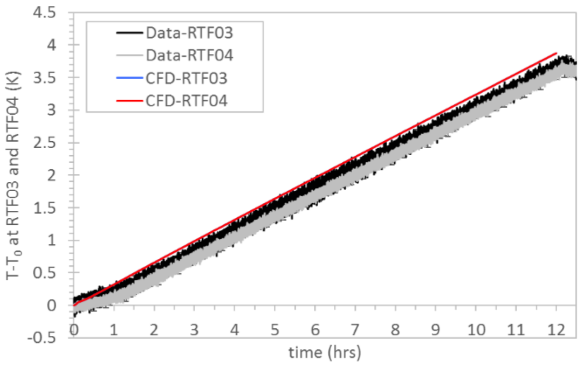
VJ Heating (3.75 W/m^2), 70%, Self-Pressurization: { $Ra_L \rightarrow (10)^{11}$, $Ra_V \rightarrow (10)^{8}$ }

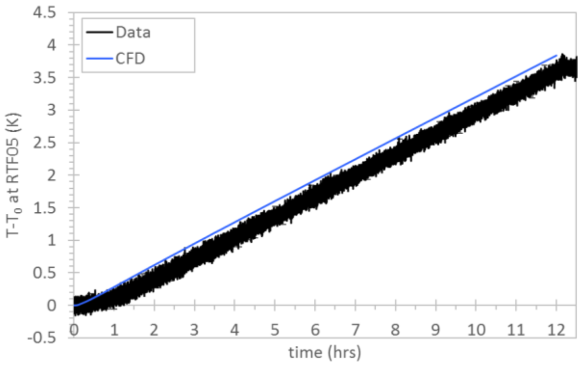


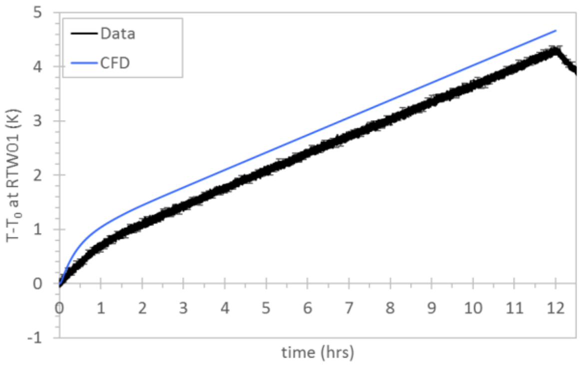


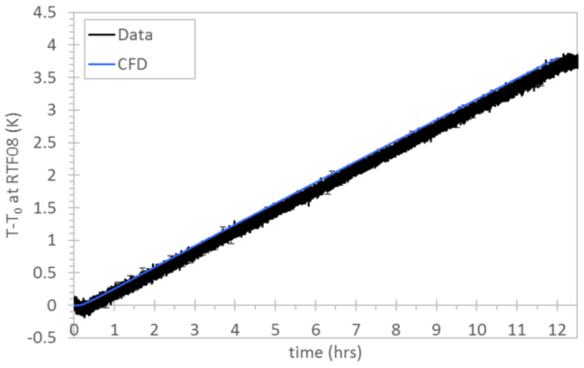






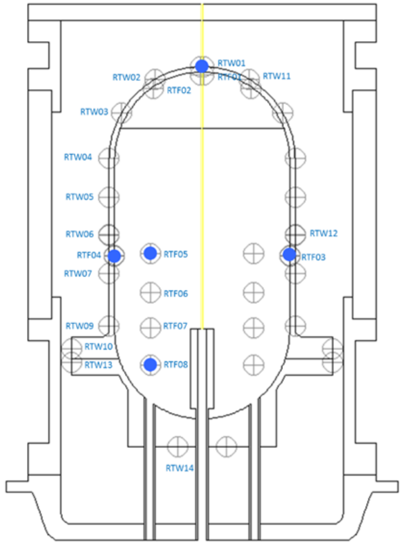


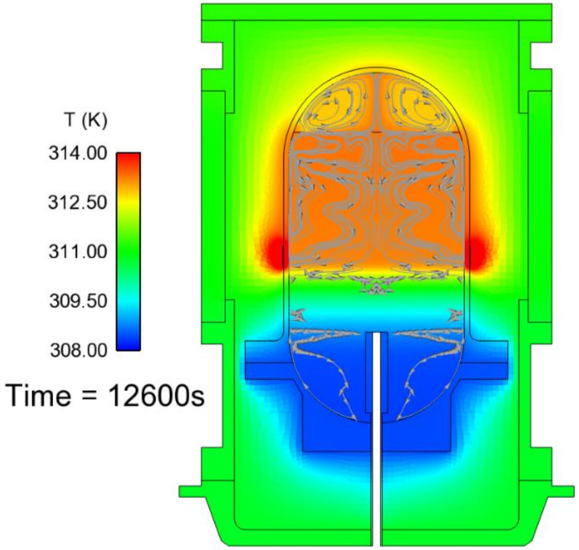


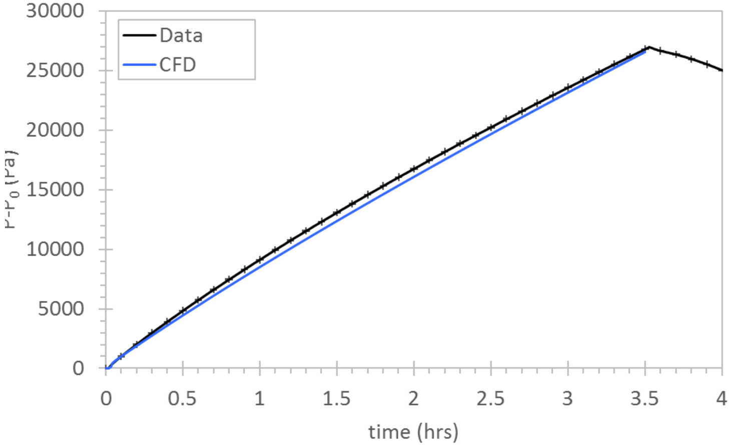


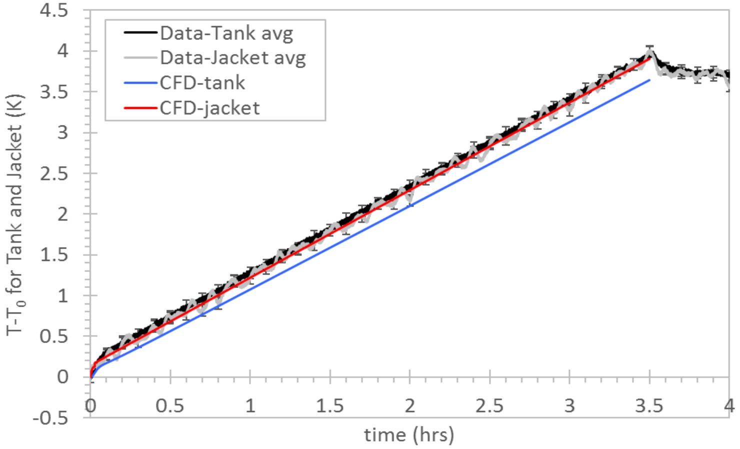
Ground Based Model Validation Experiment in Flight Hardware: 1G Self-Pressurization – Strip Band Heating

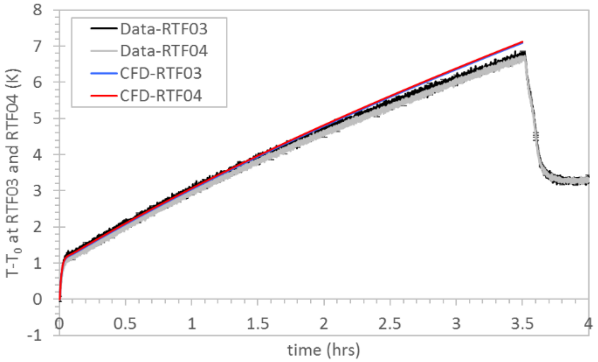
Strip Band Heating (1W), 90%, Self-Pressurization: { $Ra_L \rightarrow (10)^{11}$, $Ra_V \rightarrow (10)^{8}$ }

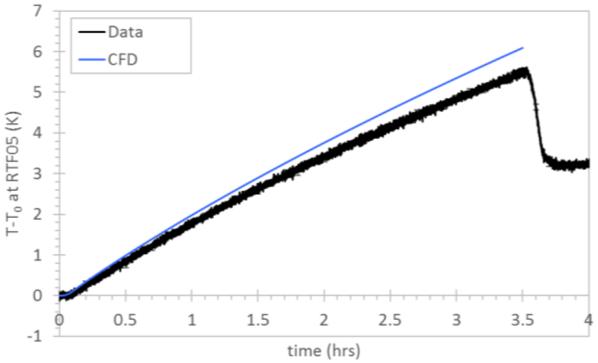


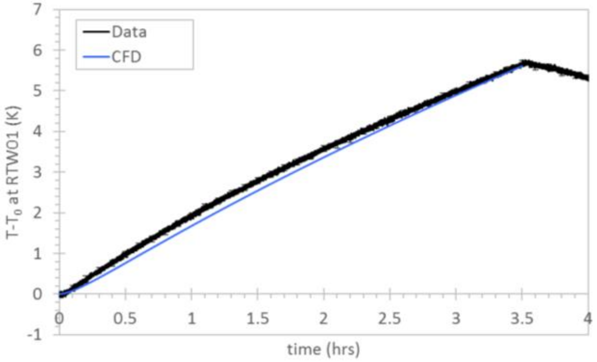


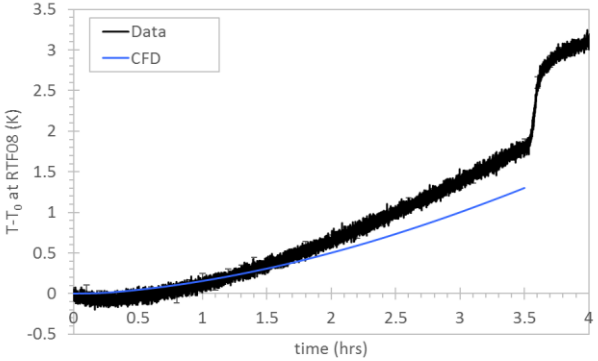






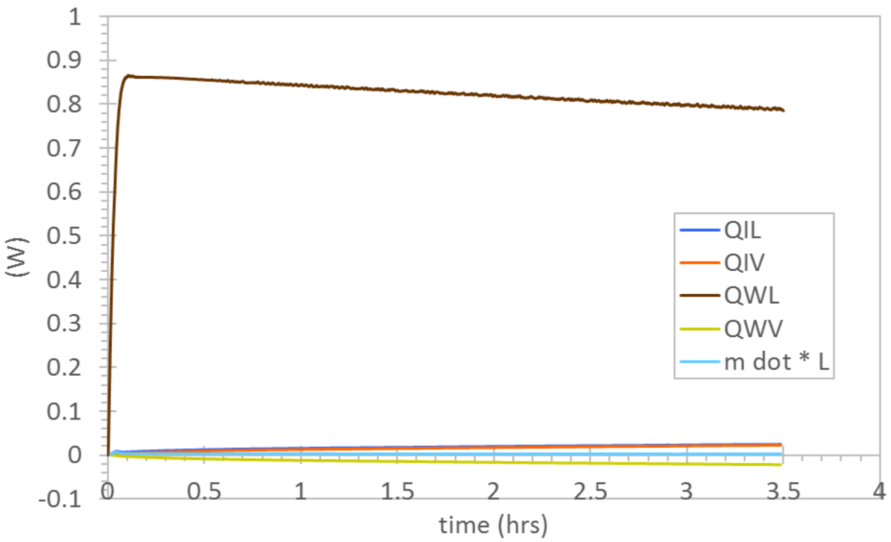


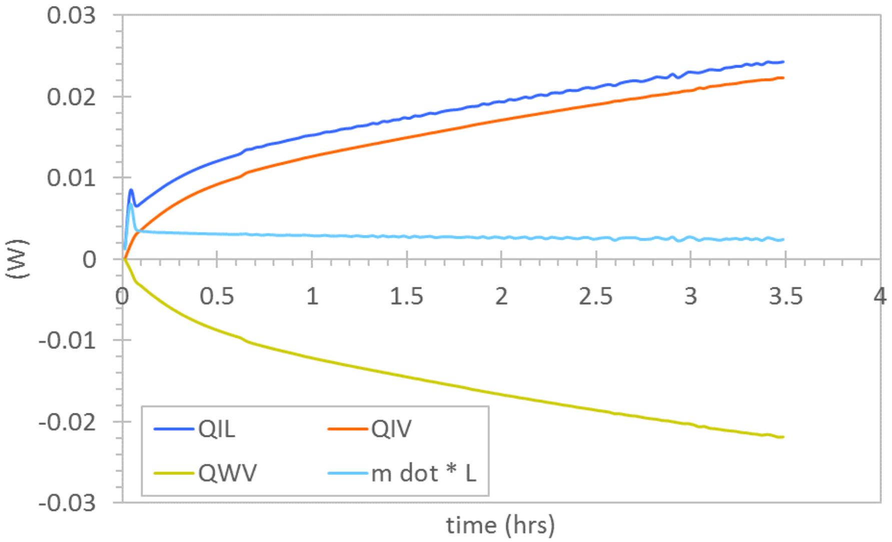


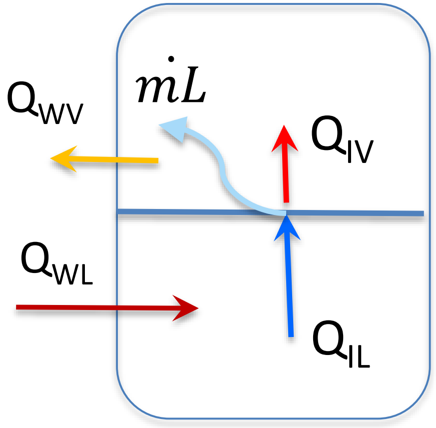


Validation Against ZBOT-Flight 1G Pressurization – Energy Flow & Distributions During SB Heating & VJ Heating

SB Heating Self-Pressurization







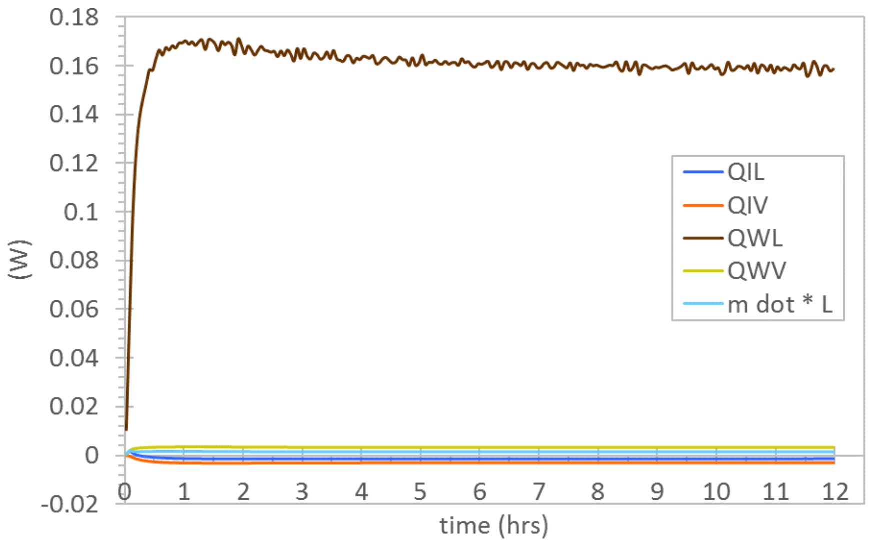
$Q_{IL} > Q_{IV}$

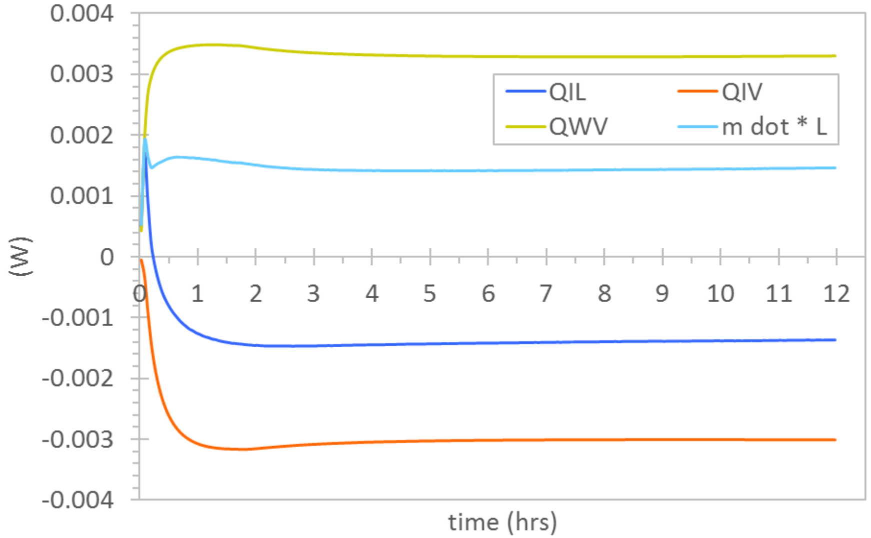
$\dot{m} > 0$

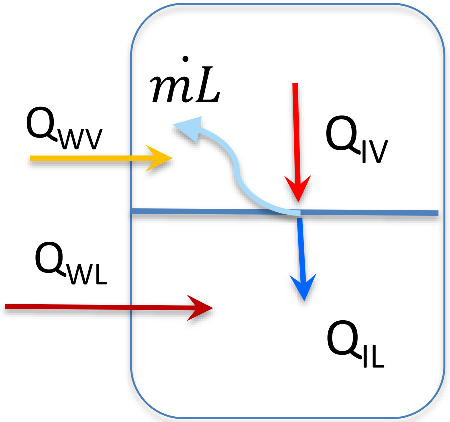
Evaporation

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

VJ Heating Self-Pressurization







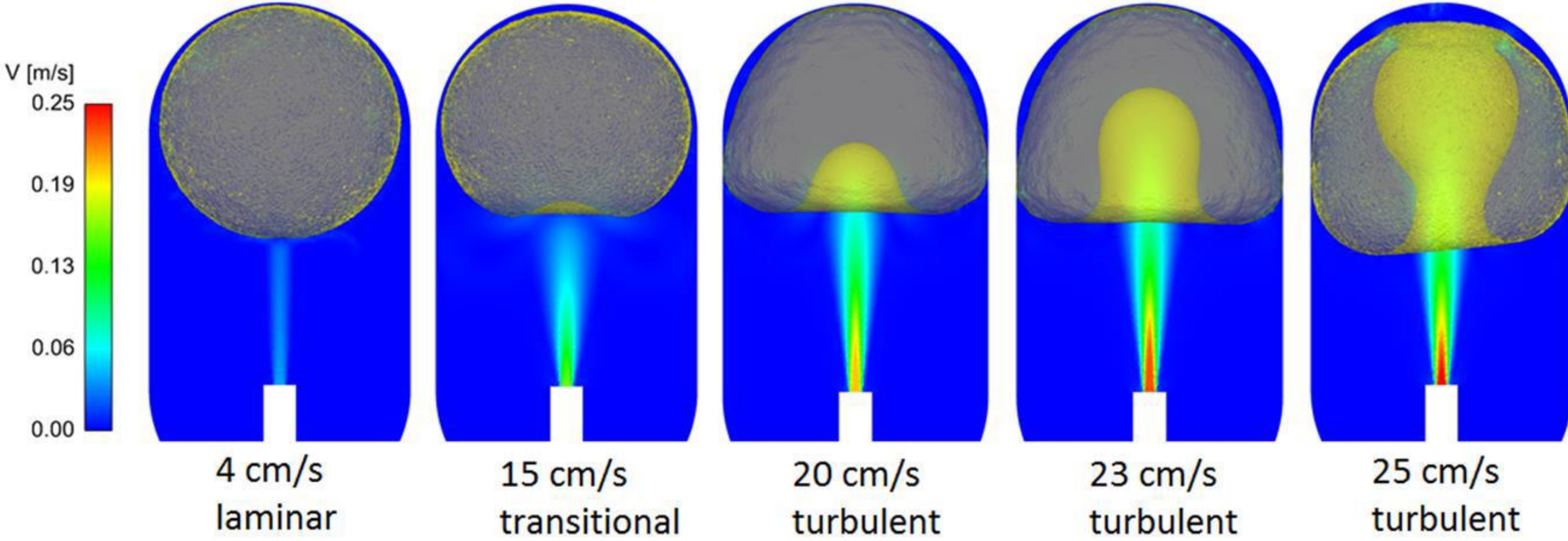
$Q_{IL} < Q_{IV}$

$\dot{m} > 0$

Evaporation

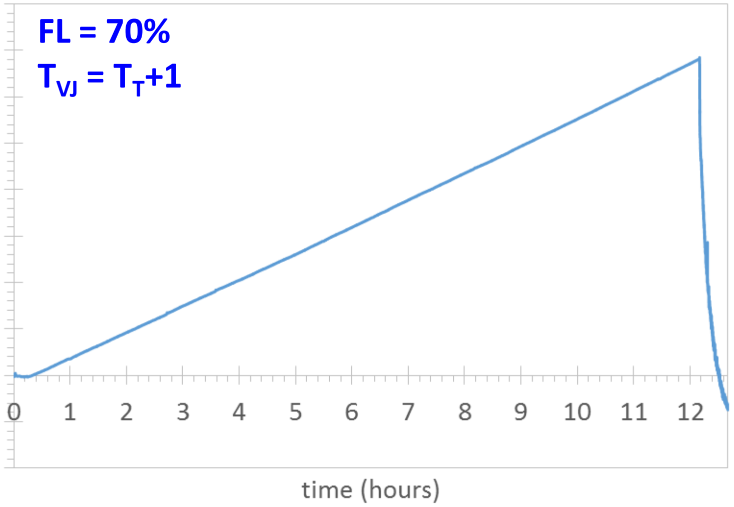
$$\dot{m}L = Q_{IL} - Q_{IV}$$

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

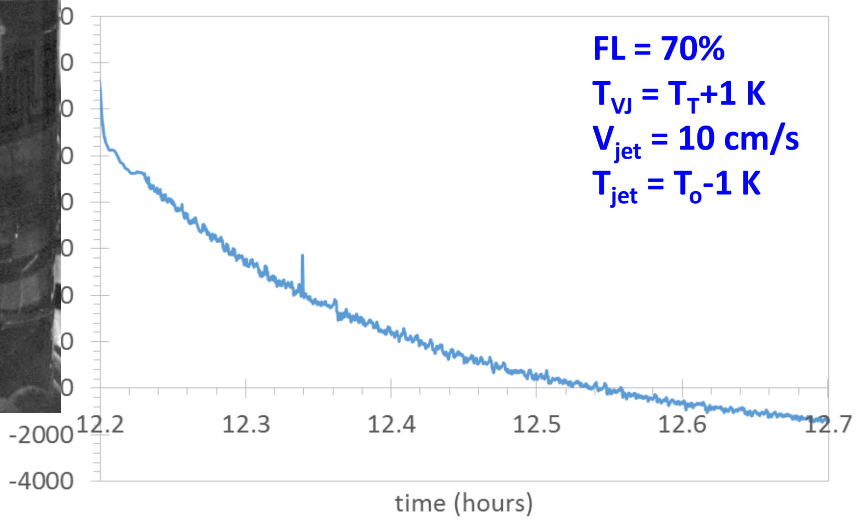


Vacuum Jacket Self-Pressurization in Microgravity - Followed by Subcooled Jet Mixing

VJ Self-Pressurization



Subcooled Jet Mixing

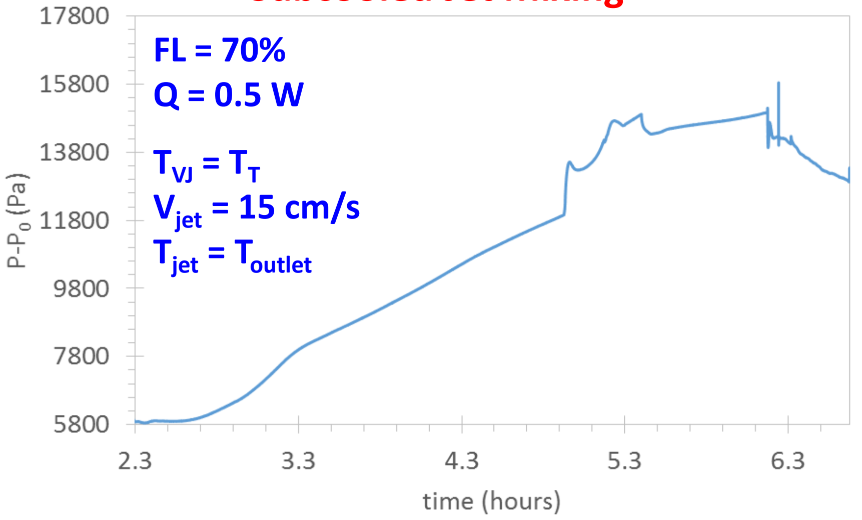


Microgravity Strip Band Heating (0.5 W) Self-Pressurization In Microgravity - Followed by Isothermal Jet Mixing

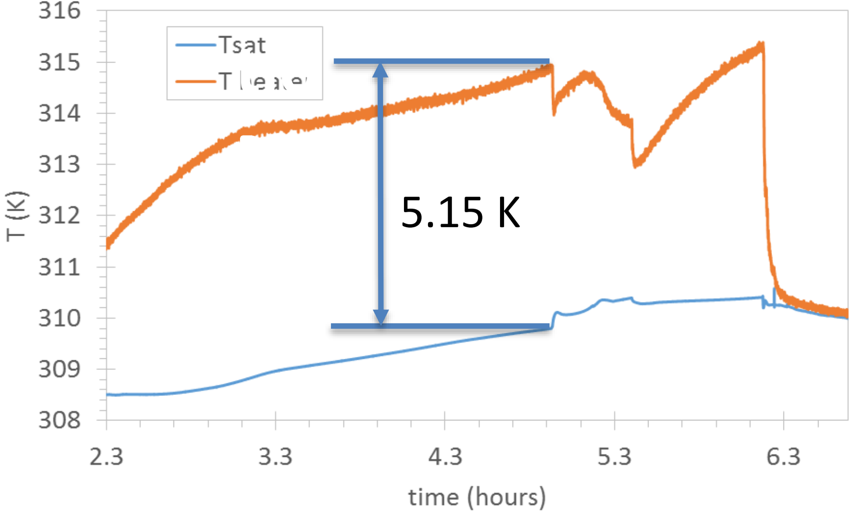
Case ZBOT-208-Self-Press-0_5W :

Case ZBOT-204-35s-PressControl-afterSelf-Press-0_5W-15cm/s

SB Self-Pressurization & Subcooled Jet Mixing



T_{Heater} & T_{Sat}

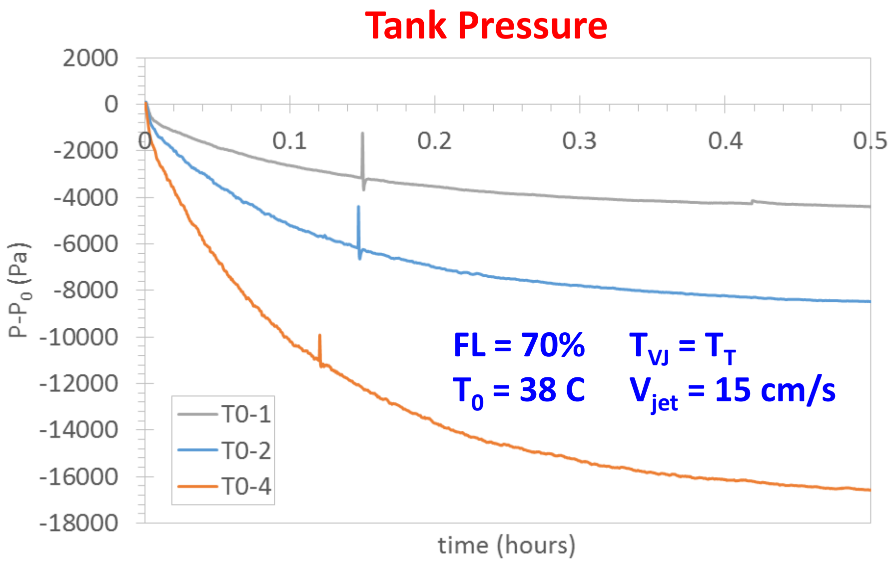


Microgravity Isothermal Jet Mixing (Without Cooling)

FL = 70%
T_0 = 38 C

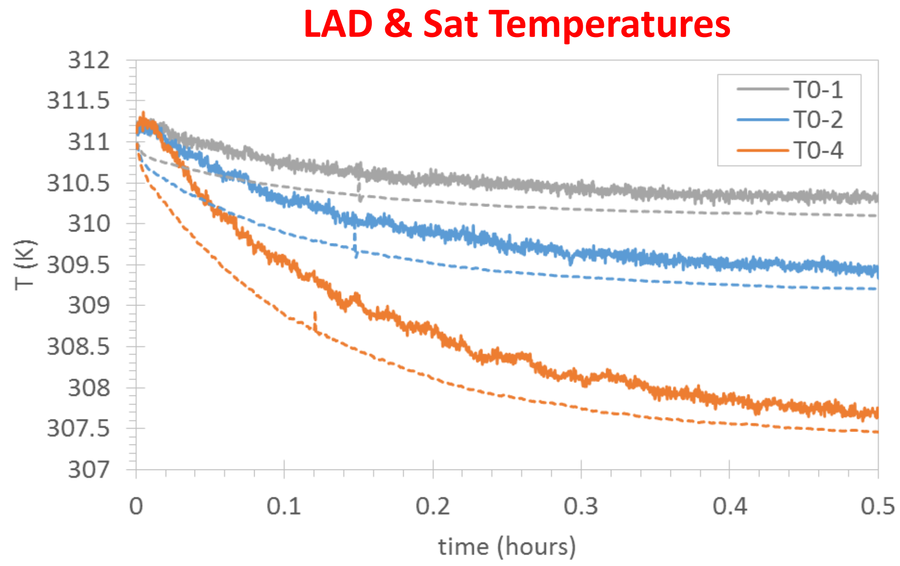
$T_{VJ} = T_T$
V_{jet} = 6, 15 cm/s
$T_{jet} = T_{outlet}$

Microgravity Subcooled Jet Mixing at Jet V = 15 cm/sec

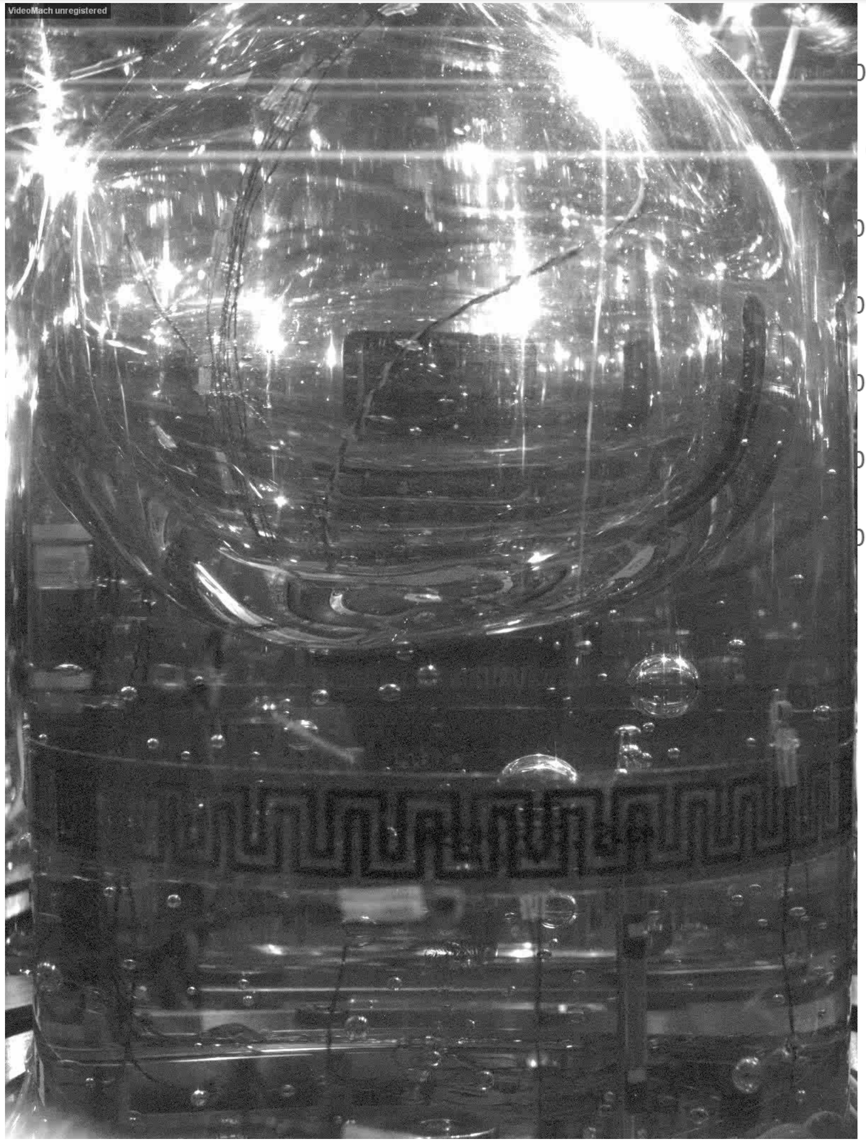

Tank Pressure

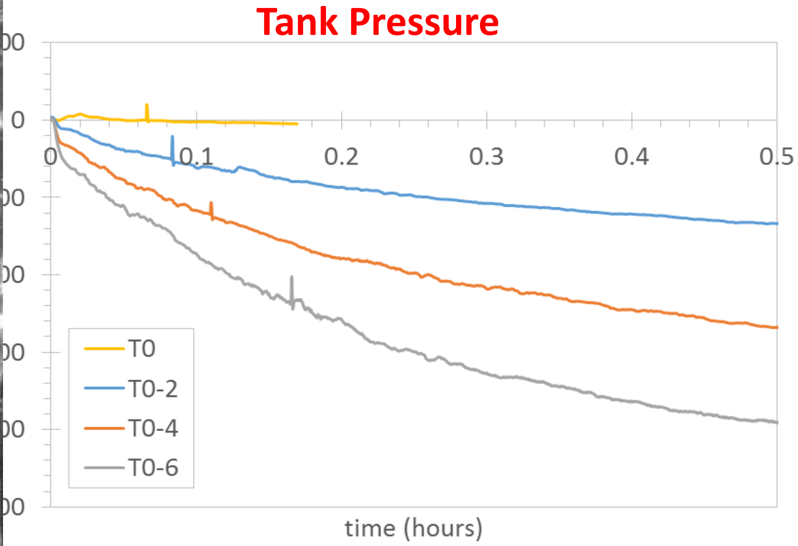
FL = 70% $T_{VJ} = T_T$

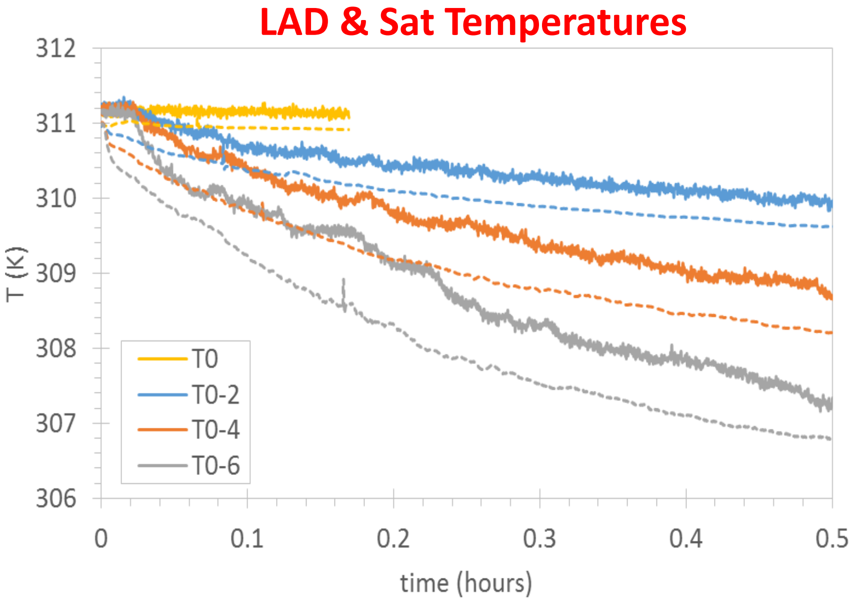
T_0 = 38 C V_{jet} = 15 cm/s

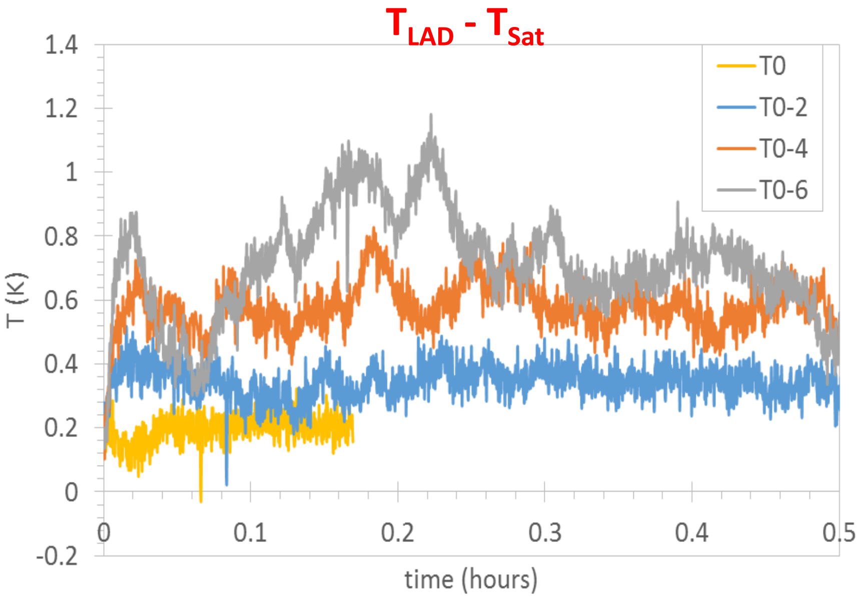

LAD & Sat Temperatures

Microgravity Subcooled Jet Mixing at Jet V = 6 cm/sec




Tank Pressure


LAD & Sat Temperatures


$T_{LAD} - T_{Sat}$

FL = 70%
T_0 = 38 C

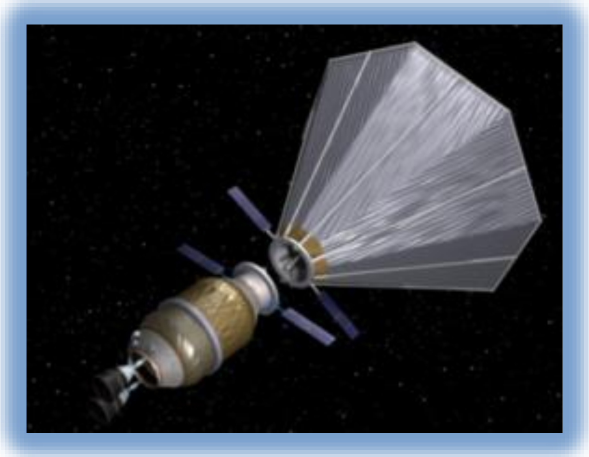
$T_{VJ} = T_T$
V_{jet} = 6 cm/s

Backup Charts

Development & Validation of Analysis Tools (DVAT) For CFM

Develop a computational platform to study and simulate the engineering performance of propellant storage tanks in 1g and microgravity with physical and numerical fidelity:

- Multiphase CFD Models: Capture the intricate two phase transport and interfacial phenomena that control tank pressurization, pressure control, filling and cryogen transfer in 1g, partial g and microgravity with physical accuracy.
- Multinode Models: Be able to predict tank engineering performance with numerical efficiency
- Coupled CFD-Multinode simulations necessary to predict tank performance during long duration (up to 1 year) missions.
- Increase capabilities of both CFD and multi-node analysis tools to perform predictive simulations of different Cryogenic Fluid Management (CFM) operations under settled and unsettled conditions for future missions:
  - Self-Pressurization
  - Pressure control (axial jet, spray bar TVS, Broad Area Cooling)
  - Pressurization (helium and autogenous, different submergence)
  - Transfer line chilldown (pulse, continuous)
  - Tank chilldown (charge-hold-vent)
  - Tank filling and draining
  - ISRU liquifaction



Cryogenic Propellant Depots (credit: ULA concept)

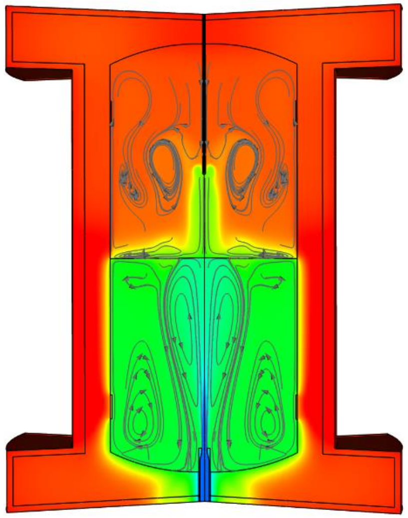
In Situ Resource Utilization (ISRU) Lox/CH4 Spacecraft Propulsion

Large Propulsion Stages

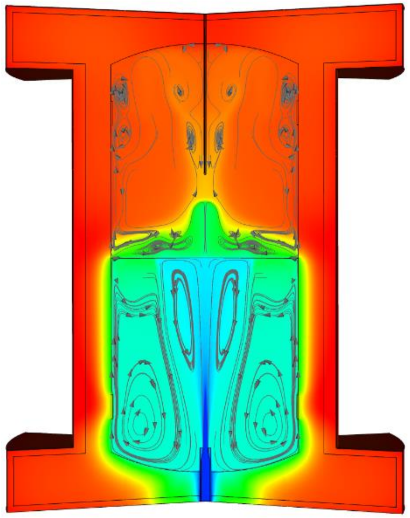
Validation Against ZBOT 1G Pressurization & Pressure Control Simulant Fluid (PnP) – Small Scale

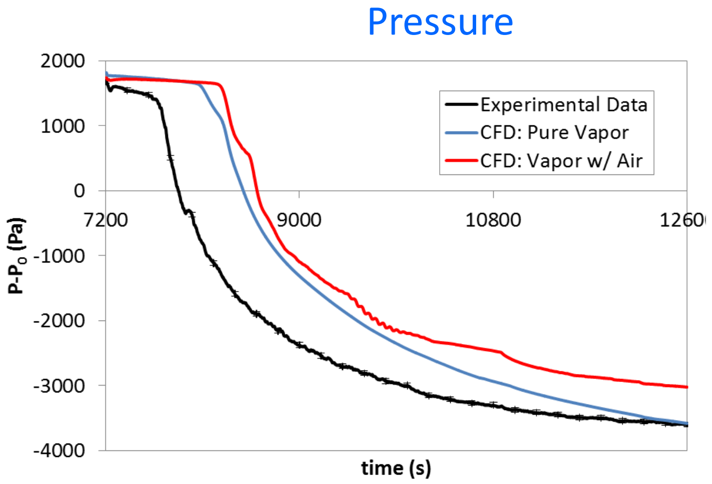
1W Strip Heater, Jet Mixing Pressure Control, Vjet = 25cm/sec, Tjet = 294 – Tliquid ~ 296

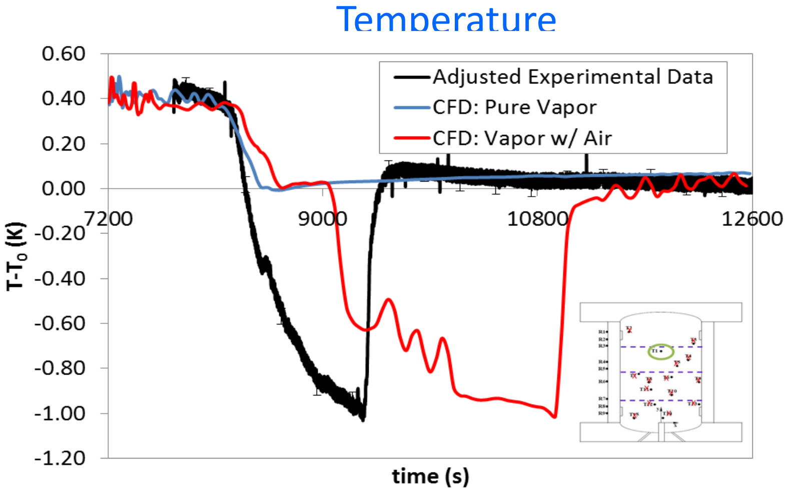
3D with air t = 10,000 s

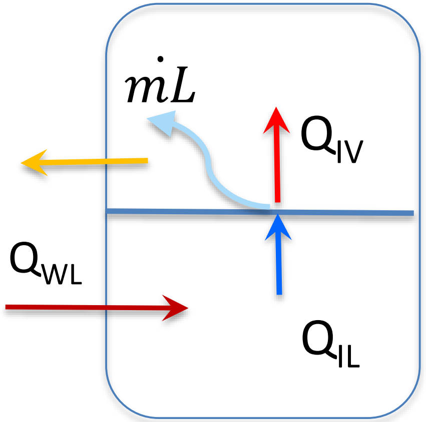


3D with air t = 11,500 s







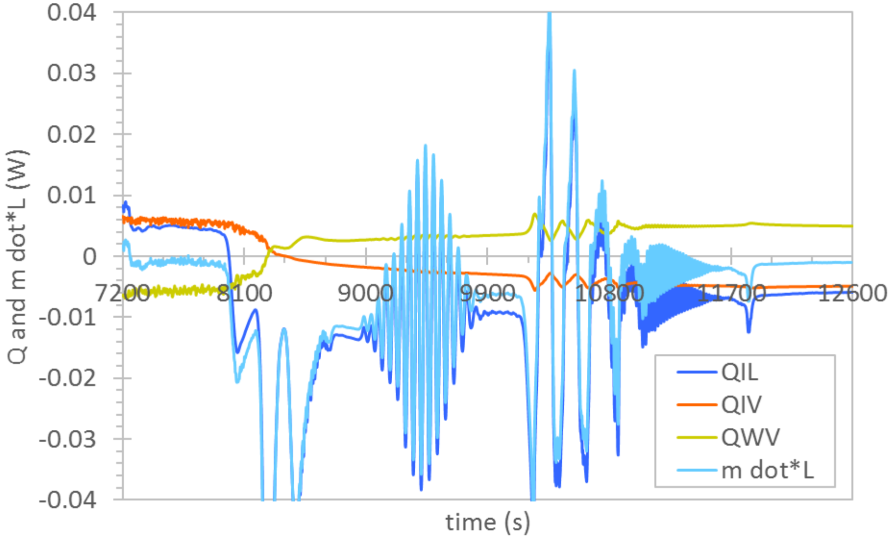


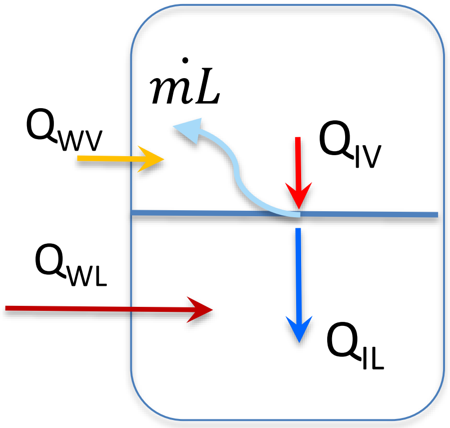
$$\dot{m}L = Q_{IL} - Q_{IV}$$

$Q_{IL} < Q_{IV}$

$\dot{m} < 0$

Condensation





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

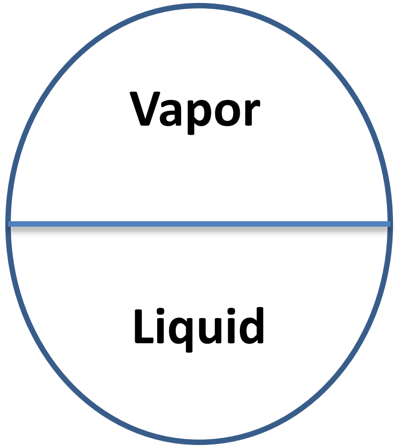
$Q_{IV} < Q_{IL}$

$\dot{m} < 0$

Condensation

Two-Phase Sharp Interface Storage Tank CFD Model

Equation	Liquid	Ullage
Continuity	√	√
Navier Stokes	√	√
Energy	√	√
Species	√	√
Turbulence (k-ω)	√	√



Continuity:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \vec{v}) = 0$$

Momentum:

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla(\rho \vec{v}\vec{v}) = -\nabla p + \nabla\left[\mu_{eff}\left(\nabla \vec{v} + \nabla v^{T}\right)\right] + \rho \vec{g} + \vec{F}_{vol}$$

Energy:

$$\frac{\partial}{\partial t}(\rho E) + \nabla(\vec{v}(\rho E + p)) = \nabla(k_{eff} \nabla T) + S_h$$

Species:

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

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

Interfacial Energy Balance:

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

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

Schrage Interfacial Mass Transfer:

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

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

Stefan Wind:

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

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:

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

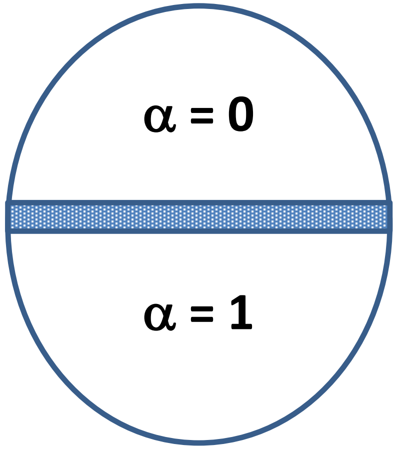
Continuity of Volume Fraction of the *q*-th phase:

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

Continuum Surface Force (Brackbill et al.):

$$F_{vol} = \sum_{\text{pairs}\, ij,\ i<j}\sigma_{ij}\frac{\alpha_i\rho_i h_j\nabla\alpha_j+\alpha_j\rho_j h_i\nabla\alpha_i}{\frac{1}{2}\left(\rho_i+\rho_j\right)}$$

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



Interfacial mass transfer per unit volume:

$$S_{\alpha_q} = \dot{\mathbf{m}}_i\cdot\mathbf{A}_{i,}\left[\frac{kg}{m^3\cdot\sec}\right]$$

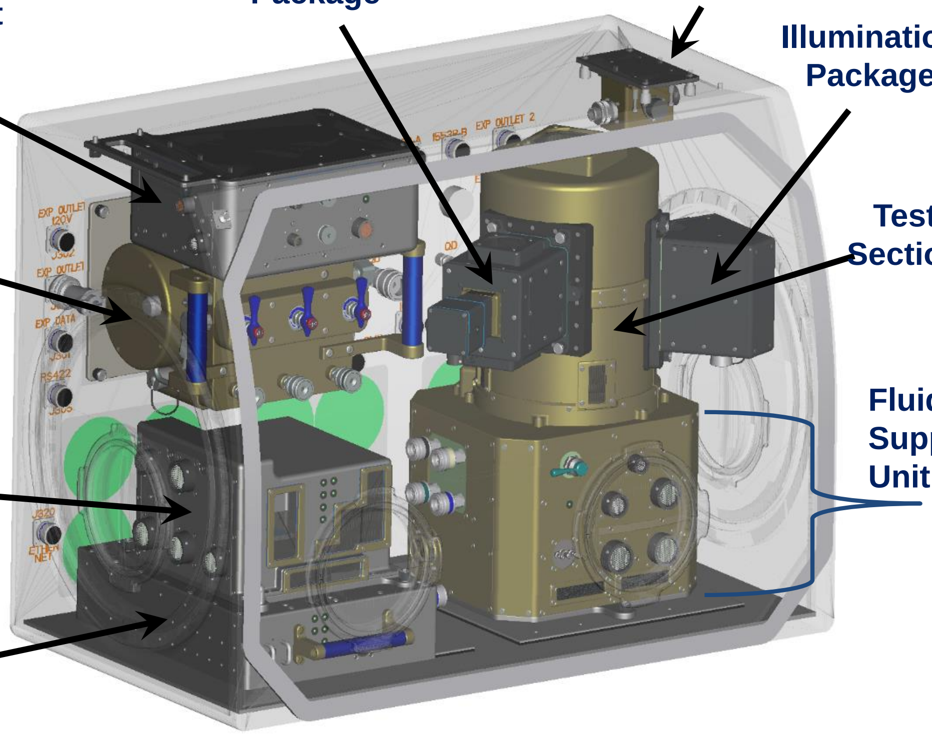
$$\mathbf{A}_i = \left|\nabla\alpha\right|,$$

$\dot{\mathbf{m}}_i$ is a mass flux vector in kg/(m^2·sec)

Schrage Interfacial Mass Transfer:

$$\dot{\mathbf{m}}_i = J_v = \frac{2\sigma}{2-\sigma}\frac{1}{\sqrt{2\pi RT_I}}\left[P_{sat}(T_I)-P_v\right]$$

K-Site & MHTB 1G LH2 Self-Pressurization: CFD Results vs Experiment – Tank Pressure, Temperature and Flow Field



Data Acquisition and Control Unit (DACU)

Camera Package

SAMS Head

Illumination Package

Fluids Reservoir (FR)

Test Section

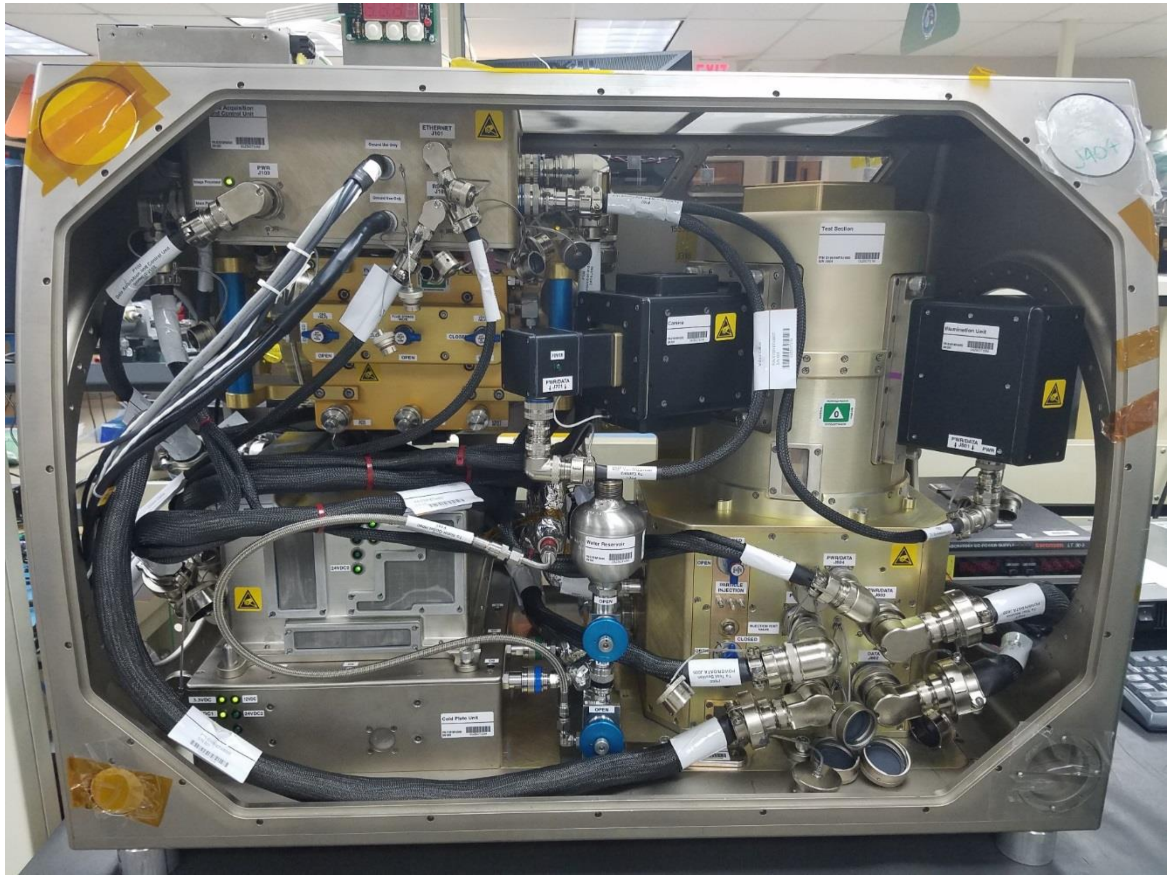
Thermal Control Unit (TCU)

Fluids Support Unit (FSU)

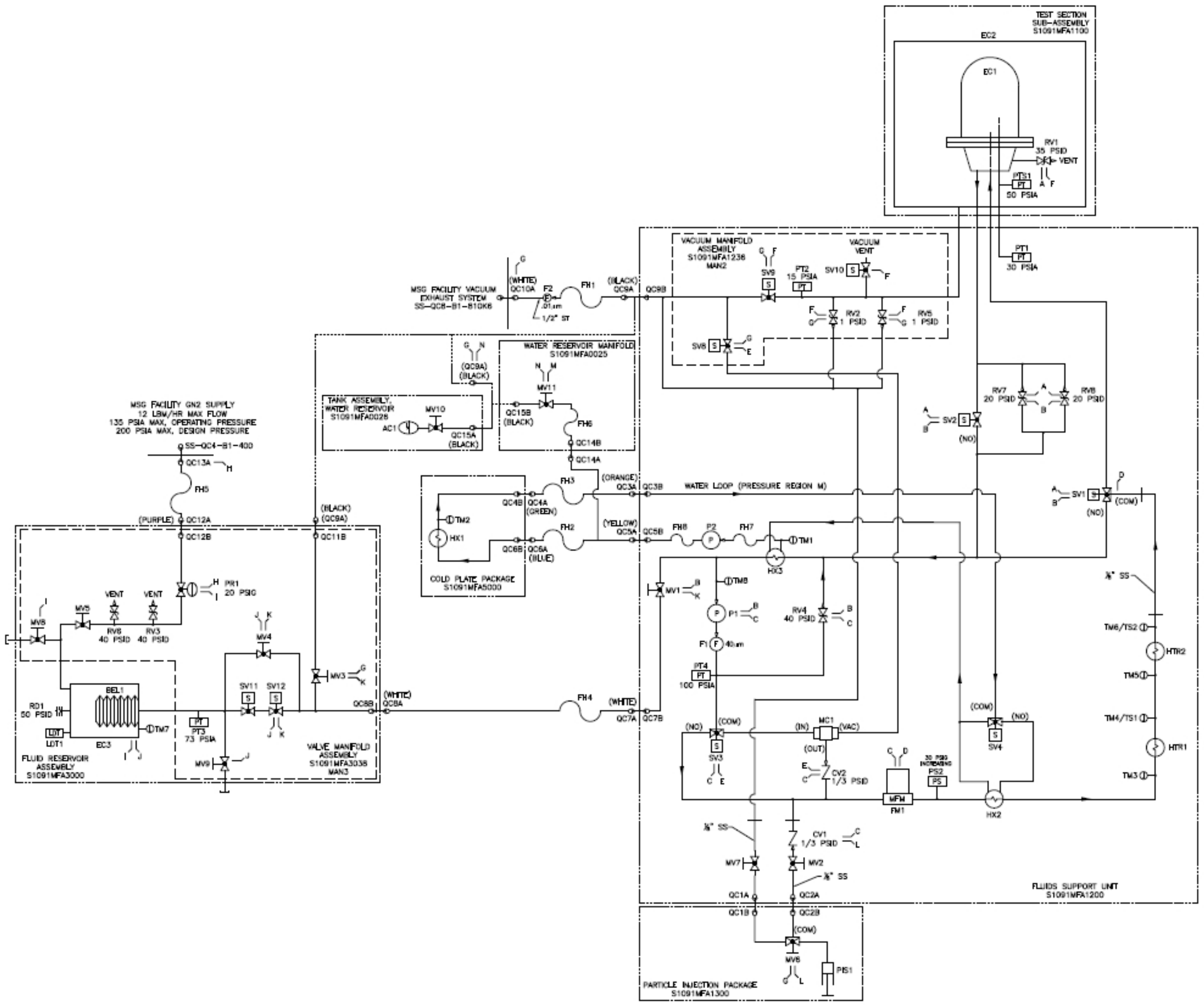
Cold Plate Package (CPP)

ZBOT Experiment: Flight Test Tank & Fluid Support Hardware

ZBOT Hardware in Microgravity Science Glovebox Mockup at NASA MFSC

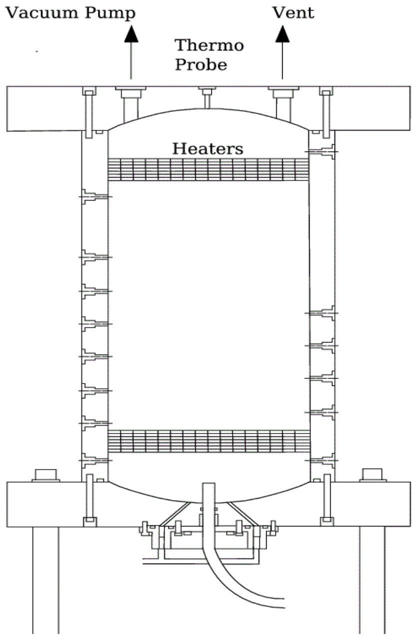


ZBOT Fluid Support Unit (FSU) & Reservor Schematic

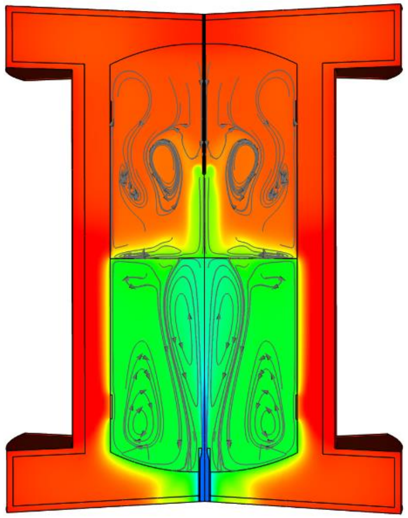


Validation Against ZBOT 1G Pressurization & Pressure Control Simulant Fluid (PnP) – Small Scale - Strip Heater

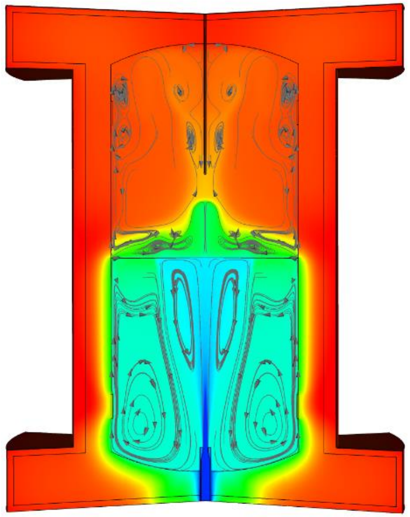
Jet Mixing Pressure Control - 20 Torr Residual Air – 2 deg Subcooled Jet



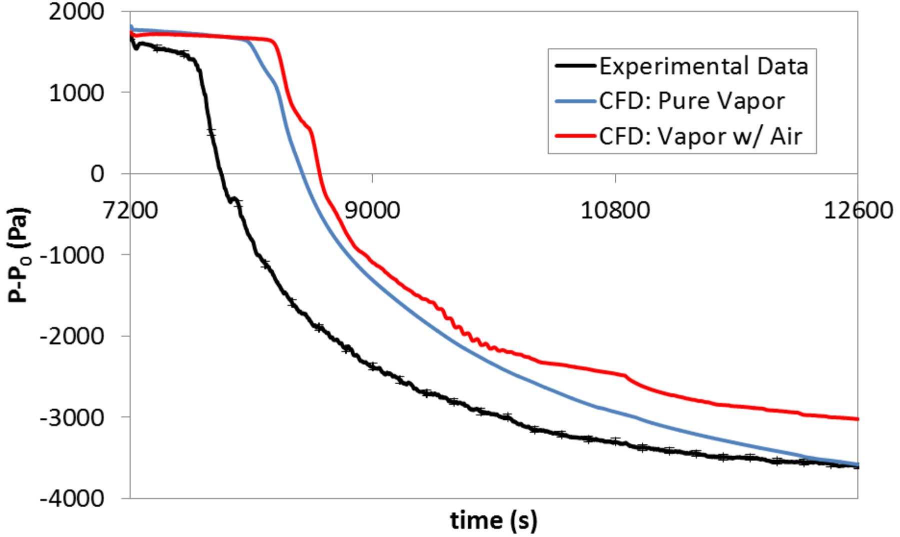
3D with air t = 10,000 s



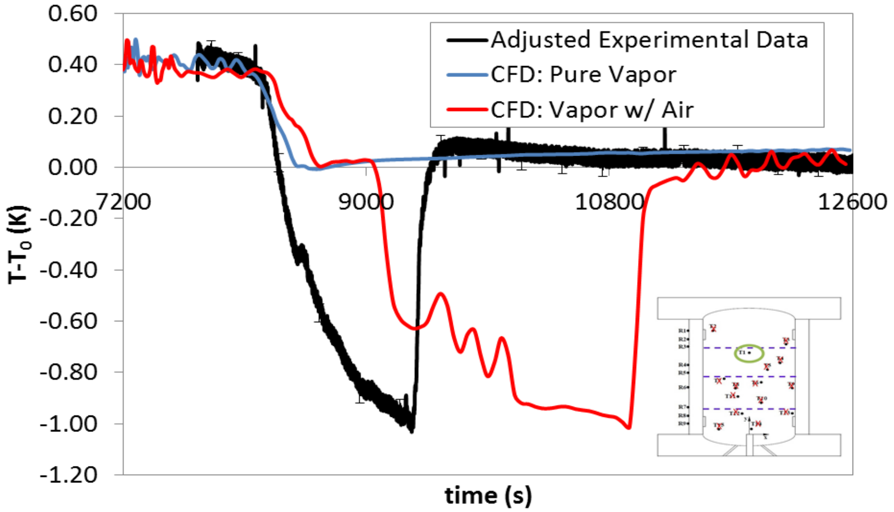
3D with air t = 11,500 s



Pressure



Temperature



Microgravity Strip Band Heating (0.1 W) Self-Pressurization In Microgravity