# Overview of NASA's Cryogenic Propellant Management Technology Development Projects and Related Numerical Simulations Research

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**Cleveland, Ohio**

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**JAXA-Univ. of Tokyo Joint Symposium on Numerical Modeling of Rocket and Spacecraft**
**Tsukuba Space Center of JAXA**

**March 23, 2016**

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## Outline

- ***Introduction to NASA Glenn Research Center***
- ***Background***
  - ***NASA motivation for cryogenic propellant technology development***
  - ***NASA cryogenic fluid management technology project support since ~2000***
  - ***eCryo Project Overview***
- ***eCryo project team's simulation capability development objectives (DVAT) and challenges***
- ***DVAT: Examples of cryogenic fluid management computational simulation problems and results***
- ***ZBOT Project Summary and Simulations***

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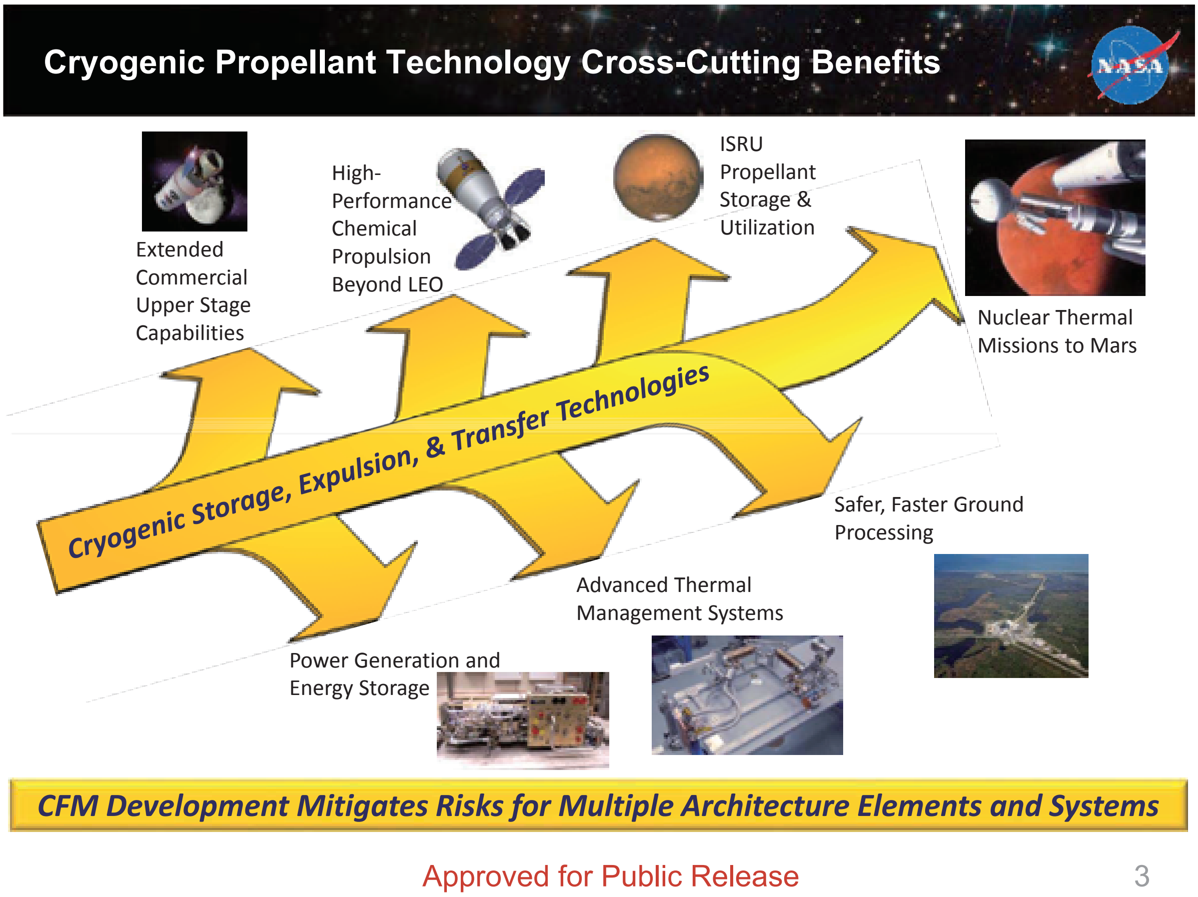
Cryogenic Propellant Technology Cross-Cutting Benefits
NASA
Extended Commercial Upper Stage Capabilities
High-Performance Chemical Propulsion Beyond LEO
ISRU Propellant Storage & Utilization
Nuclear Thermal Missions to Mars
Cryogenic Storage, Expulsion, & Transfer Technologies
Safer, Faster Ground Processing
Advanced Thermal Management Systems
Power Generation and Energy Storage
CFM Development Mitigates Risks for Multiple Architecture Elements and Systems
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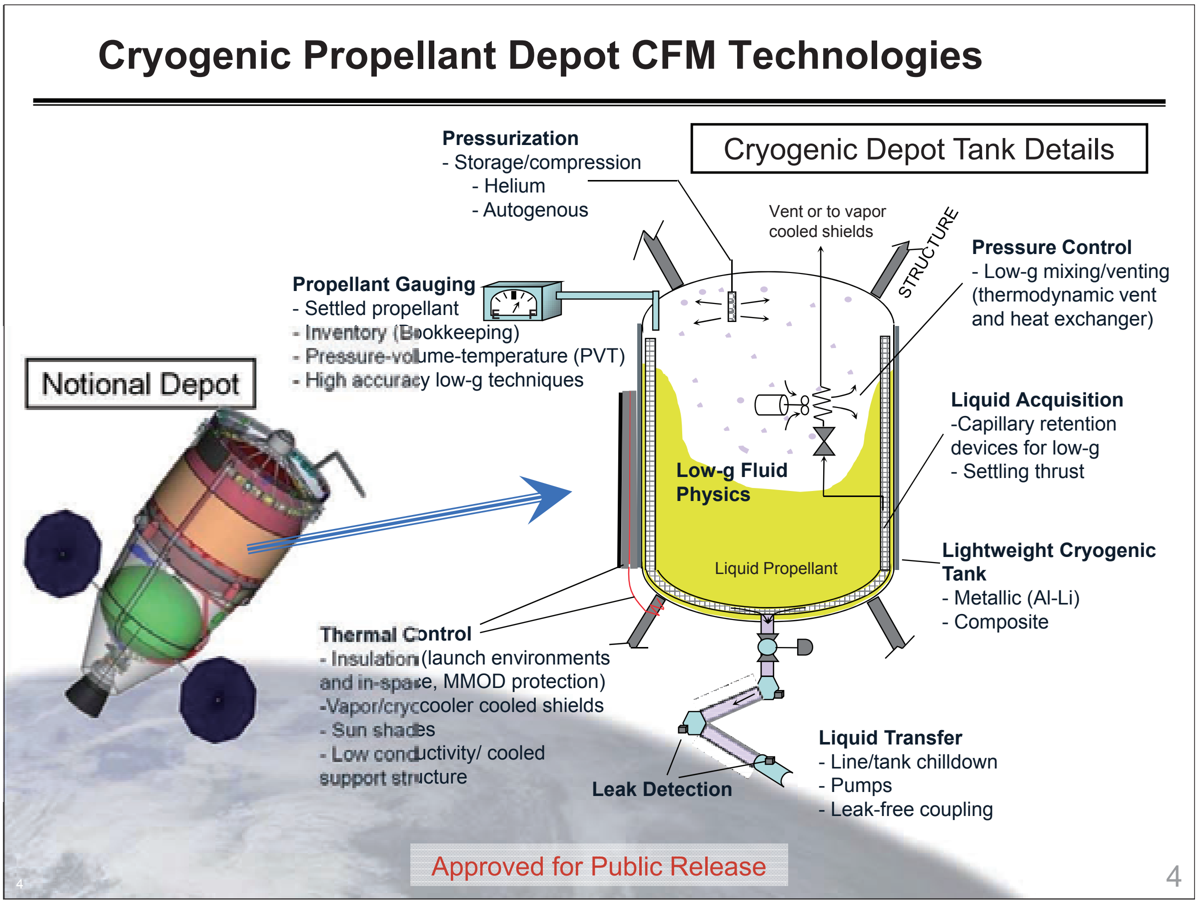
Cryogenic Propellant Depot CFM Technologies
Cryogenic Depot Tank Details
Pressurization
- Storage/compression
- Helium
- Autogenous
Vent or to vapor cooled shields
STRUCTURE
Pressure Control
- Low-g mixing/venting (thermodynamic vent and heat exchanger)
Propellant Gauging
- Settled propellant
- Inventory (Bookkeeping)
- Pressure-volume-temperature (PVT)
- High accuracy low-g techniques
Notional Depot
Liquid Acquisition
-Capillary retention devices for low-g
- Settling thrust
Low-g Fluid Physics
Liquid Propellant
Lightweight Cryogenic Tank
- Metallic (Al-Li)
- Composite
Thermal Control
- Insulation (launch environments and in-space, MMOD protection)
-Vapor/cryocooler cooled shields
- Sun shades
- Low conductivity/ cooled support structure
Leak Detection
Liquid Transfer
- Line/tank chilldown
- Pumps
- Leak-free coupling
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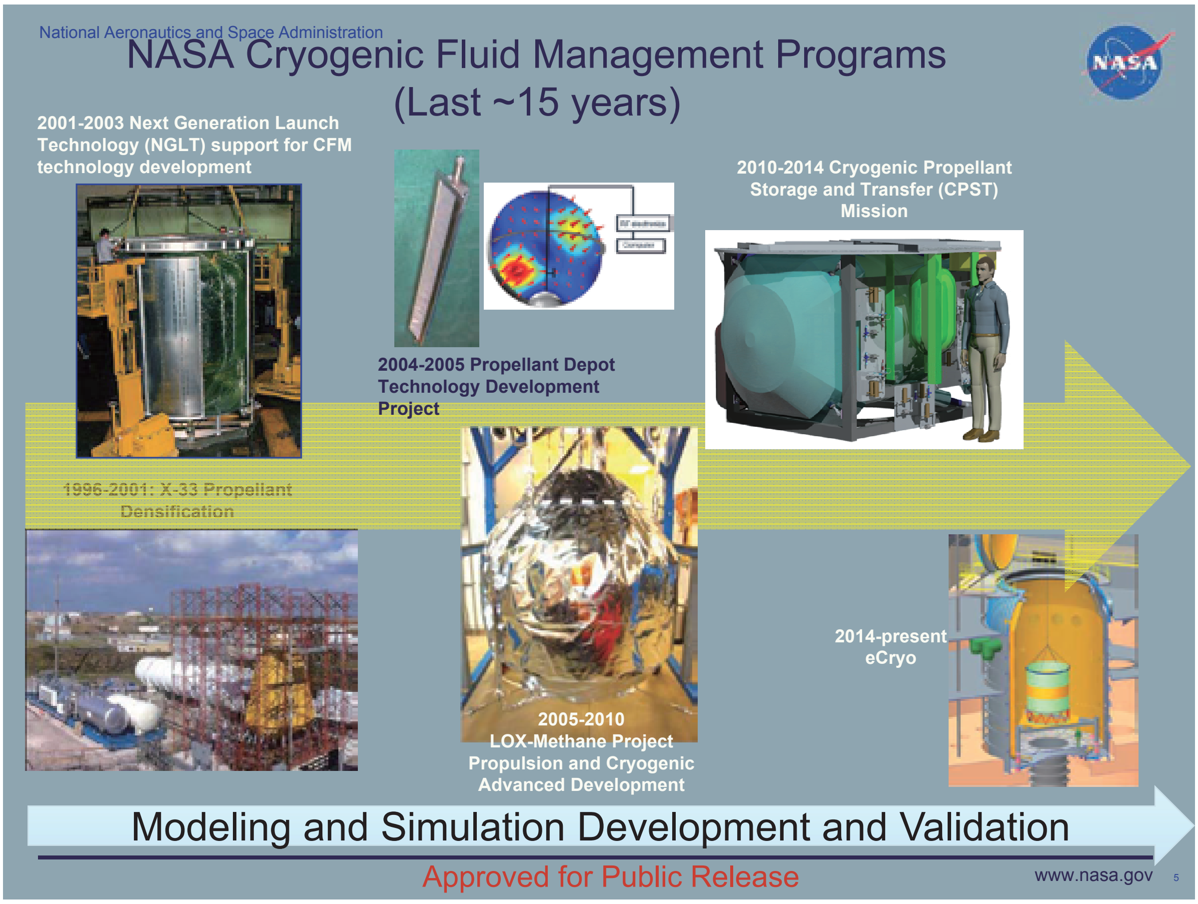
National Aeronautics and Space Administration
NASA Cryogenic Fluid Management Programs
(Last ~15 years)
2001-2003 Next Generation Launch Technology (NGLT) support for CFM technology development
2004-2005 Propellant Depot Technology Development Project
2010-2014 Cryogenic Propellant Storage and Transfer (CPST) Mission
1996-2001: X-33 Propellant Densification
2005-2010 LOX-Methane Project Propulsion and Cryogenic Advanced Development
2014-present eCryo
Modeling and Simulation Development and Validation
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National Aeronautics and Space Administration
Evolvable Cryogenics (eCryo)
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## eCryo Project Summary

**Develop, integrate, and validate cryogenic fluid management (CFM) technologies at a scale relevant to and meeting the mission needs for SLS/Stages and Exploration Missions**

### Objectives:

- Technology development for extended missions focused on the needs of the SLS/stages and Exploration missions.
- Evolutionary development of new technology demonstrating near term gains which are shared with industry.
- Increase capabilities of analysis tools to perform predictive simulations for missions with in-space cryogenic systems.

### Technology Demonstrations:

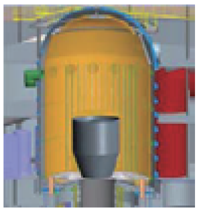
- Use existing Agency assets and infrastructure to mature cryogenic propellant technologies
  - Testing ranges from components to entire systems
  - Scale of testing will be limited only by facility capabilities.

### Team:

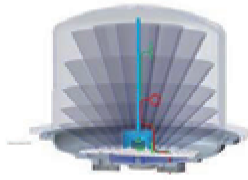
**GRC (lead)**-Project management, design, integrated analysis, CFM modeling, integration, development of Multi Layer Insulation, Radio Frequency Mass Gauge (RFMG) development, large radiant/conductive heat intercept studies, large cryogenic tank thermal and acoustic testing.

**MSFC** –Development of pressure transducers and low leakage valves for cryogenic environments, partners in analysis, modeling, cryogenic tank testing, heat intercept concepts

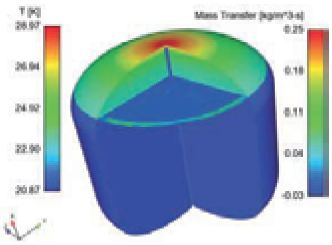
**International Partner**: CNES providing comparative analysis of computational Fluid Dynamics (CFD) for CFM.



SHIIVER Test Article



RFMG for Robotics Refueling Mission 3 (RRM3)



CFM Analysis

Space Launch Systems (SLS) Stages

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## eCryo Organizational Chart

**4.2 DVAT - Development & Validation Of Analysis Tools**
PLE: Jeffrey Moder

**4.3 IFUSI - Improved Fundamental Understanding of Super Insulation**
PLE: Wesley Johnson

**4.4 RFMG - Radio Frequency Mass Gauge for RMM3**
PLE: Gregory Zimmerli

**5.2 IVF for SLS – Integrated Vehicle Fluids for Space Launch Systems**
PLE: Arthur Werkheiser
Deputy: Monica Guzik

**5.3 SHIIVER - Structural Heat Intercept Insulation Vibration Evaluation Rig**
PLE: Joseph Zoeckler
Deputy: Lauren Ameen

**5.4 LSLF Large Scale Leakage Fixture**
PLE: Brad Addona

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# Development & Validation Of Analysis Tools (DVAT)

**Dr. Jeff Moder, Team Lead**

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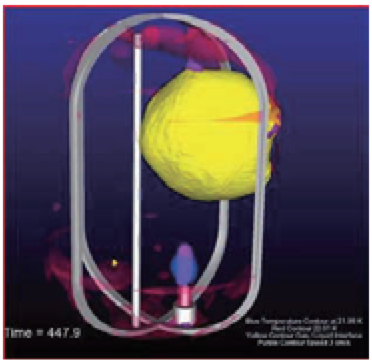
## DVAT Objectives

- Increase capabilities of Analysis Tools to perform predictive simulations of the following mission phases for in-space cryogenic systems (settled and unsettled):
  - Self-pressurization
  - Pressure control (axial jet and spray bar Thermodynamic Vent System )
  - Pressurization (helium and autogenous, various degrees of submergence)
  - Transfer line chilldown (pulse, continuous) & tank chilldown (charge-hold-vent)
  - Tank filling and draining

- Required analysis tool capabilities include:
  - Radiation and conduction **heat transfer** to calculate heat loads into cryogenic propellant tanks or transfer lines
  - **Fluid dynamics and thermodynamics** occurring within cryogenic propellant tanks or transfer lines

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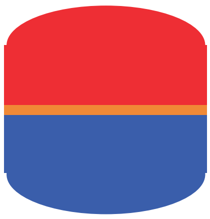
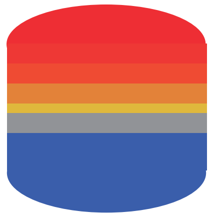
# Multinode versus CFD

Typical temperature contours are shown below for settled conditions. Tanks walls and insulation can also be included (as nodes or grids).



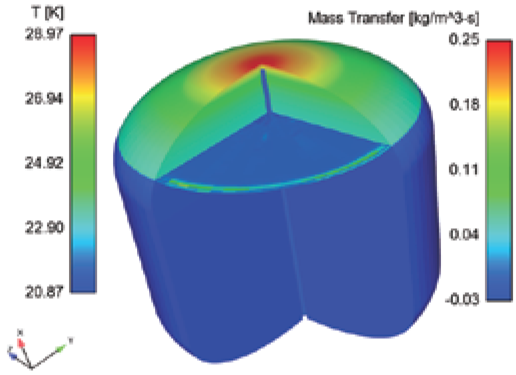
Multinode with one ullage, one liquid, one interface node (TankSIM, CPPPO)



Multinode with multiple ullage & liquid nodes (SINDA/FLUINT, GFSSP)

Alok Majumdar
Andre Leclair

Barbara
Sakowksi




CFD using 2D-axisymmetric or 3D grids (Flow-3D, Fluent)

Kevin
Breisacher

Mo Kassemi,
Olga Kartuzova
Mark Stewart

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# DVAT Rationale

- Validated Analysis Tools will reduce the development cost and risk for future NASA Exploration missions employing in-space cryogenic storage and transfer systems
- Significant validation was performed in previous CFM projects for 1g (settled) self-pressurization and axial jet mixing and TVS. Some validation was performed for 1g (settled) spray bar mixing and TVS.
- CNES CFD Benchmark collaboration included validation of 1g and low-g LN2 sloshing and LO2 boiling in zero-g.
- Further development and validation of multinode and CFD is required for unsettled conditions, and for transfer and pressurization operations in settled and unsettled conditions
- Predicting the dynamics of liquid/ullage interface position and shape during unsettled conditions, or during jet mixing or some pressurization methods where deformation or breakup of liquid/ullage interface occurs, currently requires computational fluid dynamics (CFD)
- Develop both multinode and CFD in order to eventually enable end-to-end mission simulation for mission durations of days to weeks to months.

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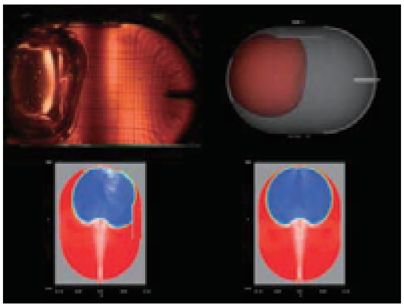
# DVAT Approach

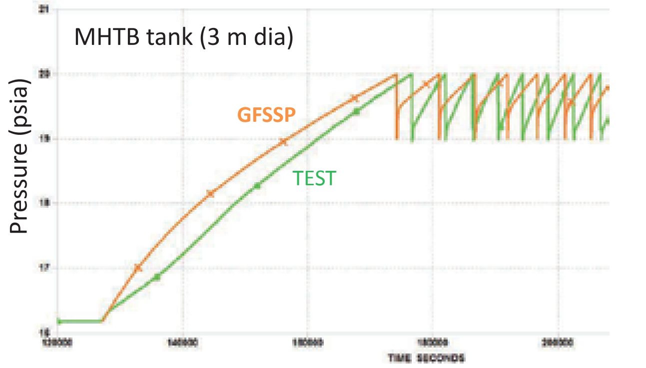
- Apply **existing thermal analysis tools** (e.g. Thermal Desktop) and **updated models for MLI and thermal strap** heat transfer to calculate **heat loads** into propellant tanks
- Develop and validate **multinode and CFD** analysis tools for simulating the **fluid dynamics and thermodynamics** occurring within tanks and transfer lines under settled and unsettled conditions
- Validate tools against cryogenic **ground test data** (settled conditions) and **subscale micro-g flight data** (unsettled conditions)

STS-43 TPCE Test Run 11



25.4 cm diameter tank, Freon 113

GFSSP simulation of 1g LH2 self-pressurization & TVS

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# DVAT Schedule – Key Activities

## Planned Efforts 2016-2019

Complete CNES CFD Benchmark Collaboration (Complete)

Extend multinode Tool capabilities to unsettled conditions

TPCE, ZBOT, RRM3, – Validate multinode and CFD Tools against small-scale micro-g flight data

Existing data – Validate CFD Tools against 1g pressurization data (submerged/un-submerged diffuser)

Existing data – Validate Tools against 1g Transfer Line and Tank Chilldown/Fill Experiments

SHIIVER – Validate Tools against Large Scale Ground Tests

↑ Indicates test data used for tool validation

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## Challenges

- Turbulence interaction with liquid/ullage interface heat and mass transfer
  - LES 2-phase (such as VOF) might improve current URANS simulation accuracy, but we need appropriate subgrid scale models for heat and mass transfer along liquid/ullage interface (from DNS, fundamental experiments, … )
  - Similar need for drop/ullage interations.
  - Note that for cryogenic tanks, we have a gas that is either 100% or mostly the vapor form of the liquid, in contrast to many other evaporation, condensation, boiling applications (where vapor of the liquid is a very small concentration of the gas surrounding the liquid)
- Improved kinetics relationships for mass transfer along liquid/ullage interface
  - Does H2 behave differently than LO2, LN2, LCH4
  - Can we do better than Schrage or Ti=Tsat(P)
- Bulk boiling and condensation models for a range of fluids and acceleration levels
- Closed tank, Laminar Rayleigh number, evaporation and/or condensation experiments with detailed pressure and temperature (near interface) measurements for H2, O2, N2, and/or CH4
- Methods to go from CFD simulations to simpler reduced-order or multinode models for long duration mission simulations (such as weeks to months of in-space CFM system storage/operation).
- In-space CFM experiments at right scale and duration (this is a funding issue, not a technical challenge).

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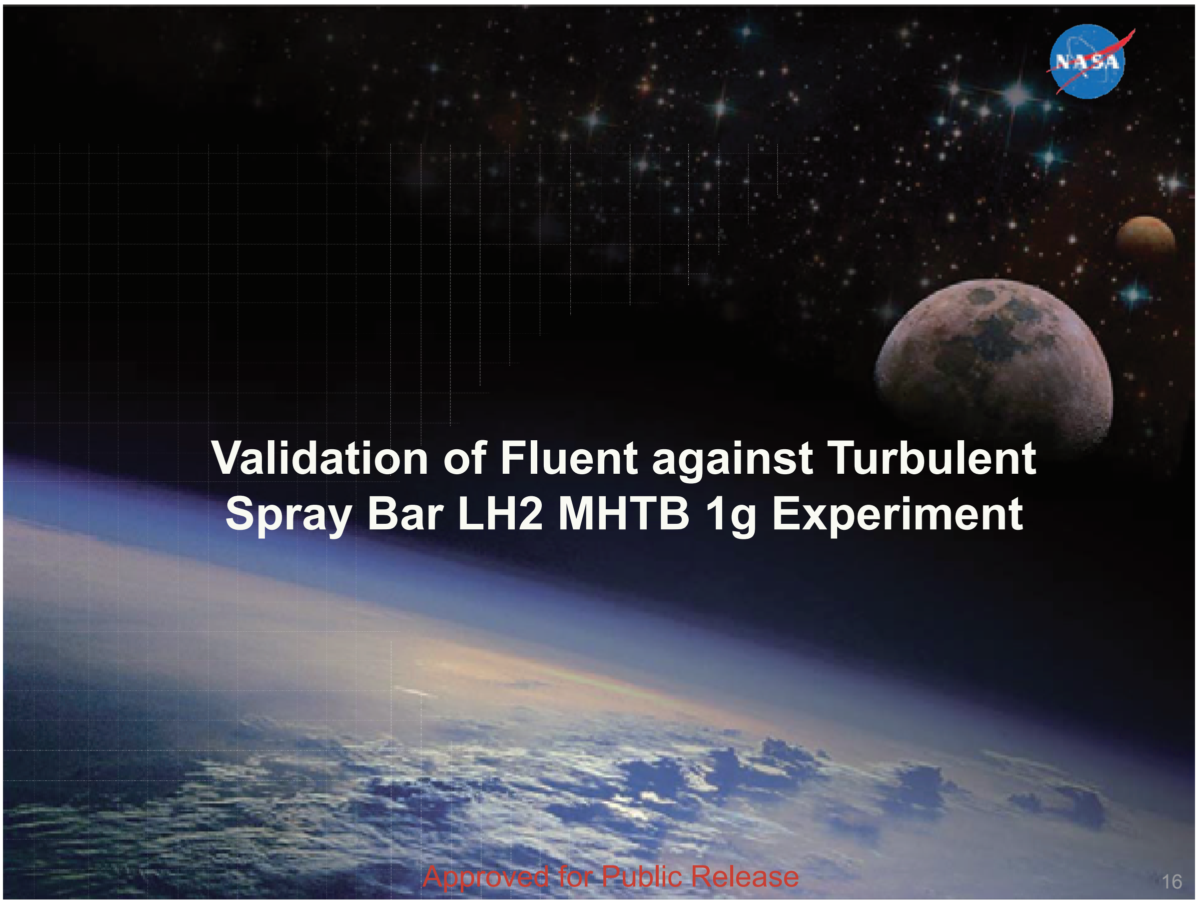


# Problem Description: Experiment

**Multipurpose Hydrogen Test Bed (MHTB)**

Tank Internal volume = 37.5 $m^3$

Cylindrical midsection with:

- height = 3.05 m
- diameter = 3.05 m

2:1 elliptical end caps

Tank is enclosed in a vacuum shroud

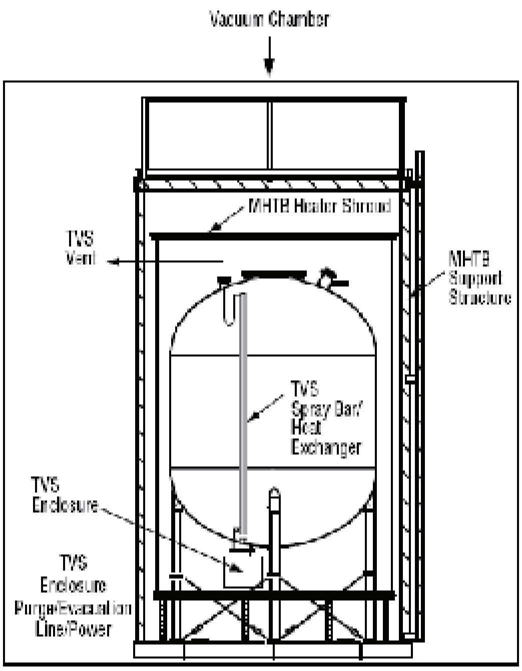
4 vertically oriented spray bar tubes attached to center tube heat exchanger

NASA TM-212926, 2003

**VOF**

Ran in parallel using Linux cluster on 10 processors

**Goal of this work is to simulate the initial self-pressurization followed by the first spray on/off cycle using ANSYS Fluent Lagrangian Spray model combined with in-house developed UDFs**

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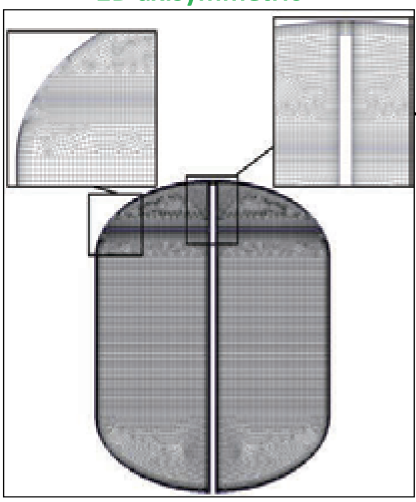
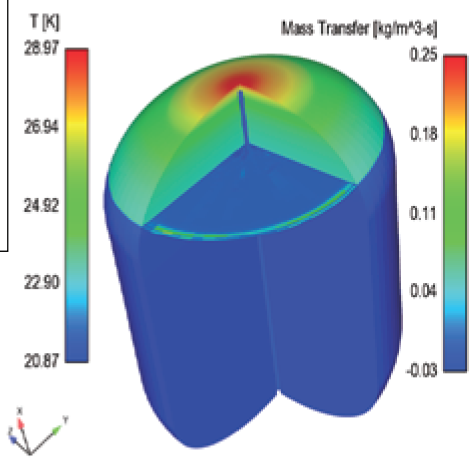
# Problem Description: Modeling Approach

2D axisymmetric



Before starting spray run, 2D-axi results were interpolated to 3D grid and self-pressurization continued for a short time to ensure a smooth transition

3D 90° sector




- Self-pressurization simulation performed on 2D-axisymmetric grid.
- Spray Bar Mixing simulation will use 3D 90° sector grid.
- Spray-Bar/Heat Exchanger assembly is approximated as lying along centerline

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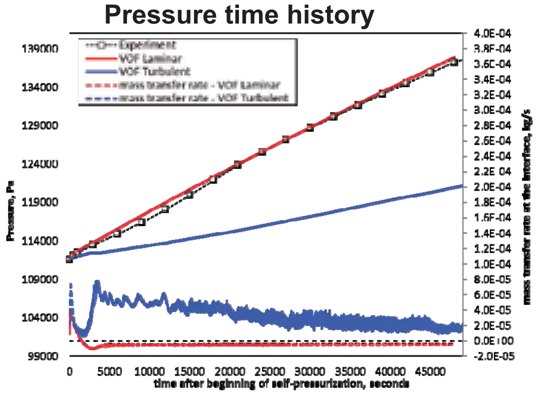
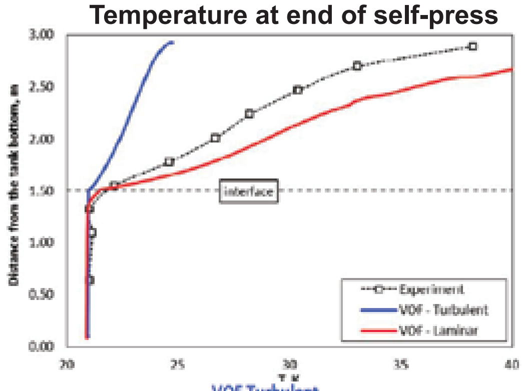
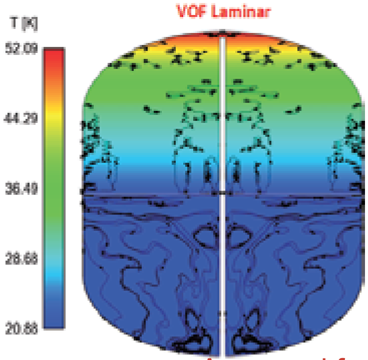
## CFD Self-Pressurization Results: Laminar vs. Turbulent

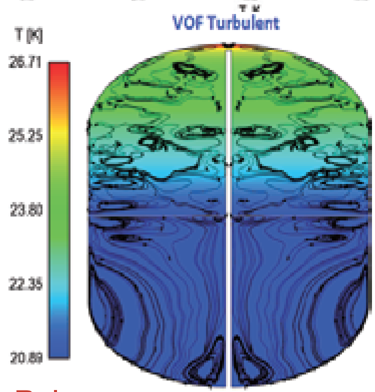
### Pressure time history




### Temperature at end of self-press

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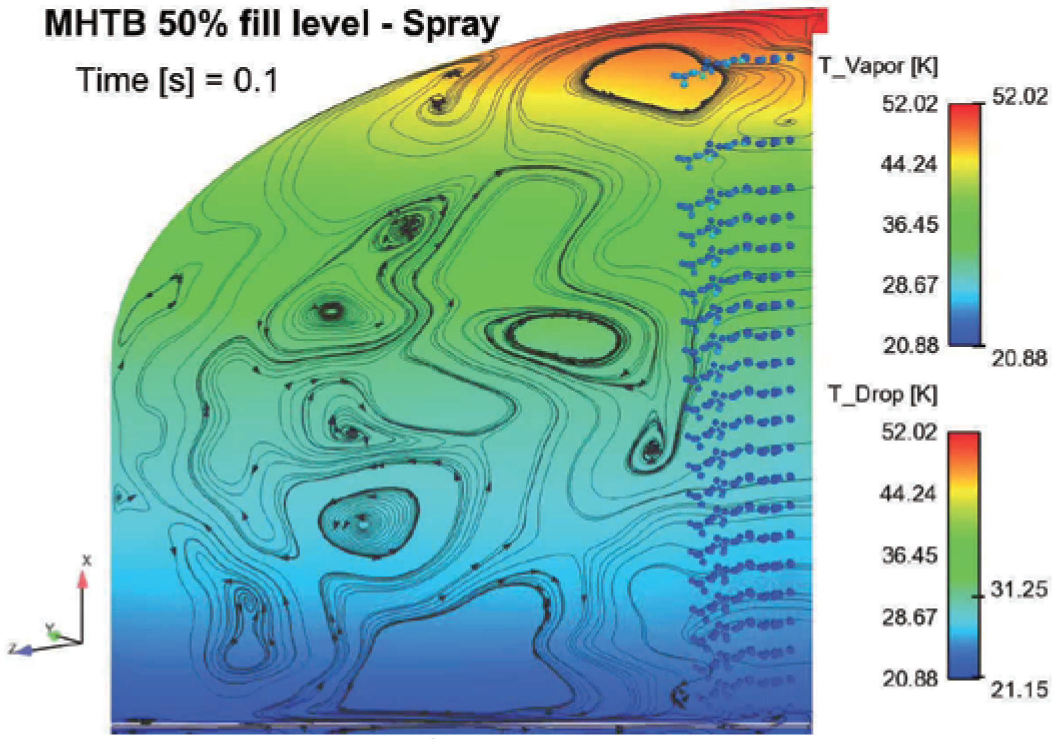
## MHTB Spray Bar Mixing Simulations

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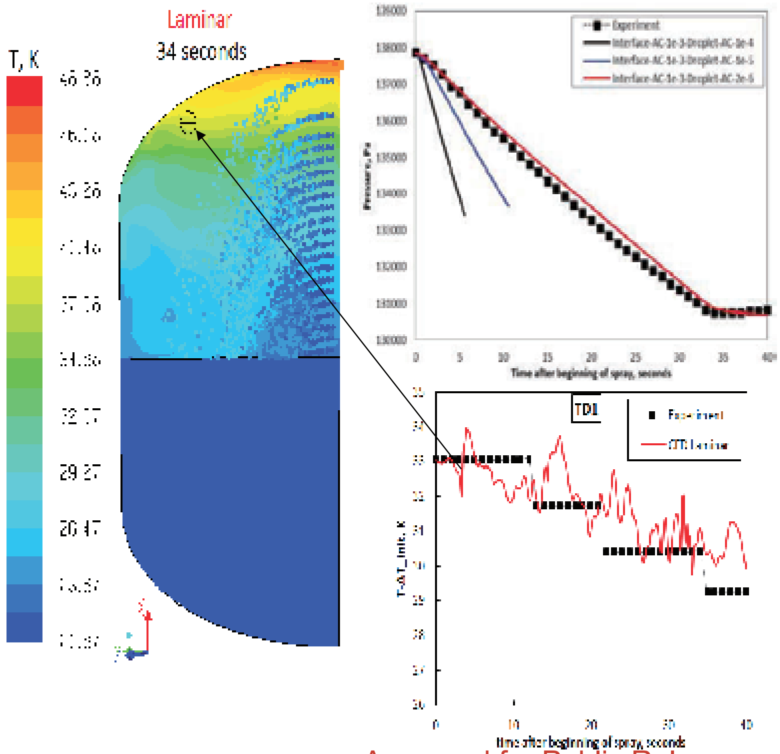
# CFD Results: axial droplet spray with Schrage droplet phase change mass transfer model




## 50% Fill Ratio

- $\sigma_e = \sigma_c$ = 1.0e-03
- $\sigma_{droplet}$ = 2.0e-06
- Laminar
- Spray on for 39 sec.
- First 3 sec of pump on with $T_{spray} > T_{sat}(P)$ were neglected

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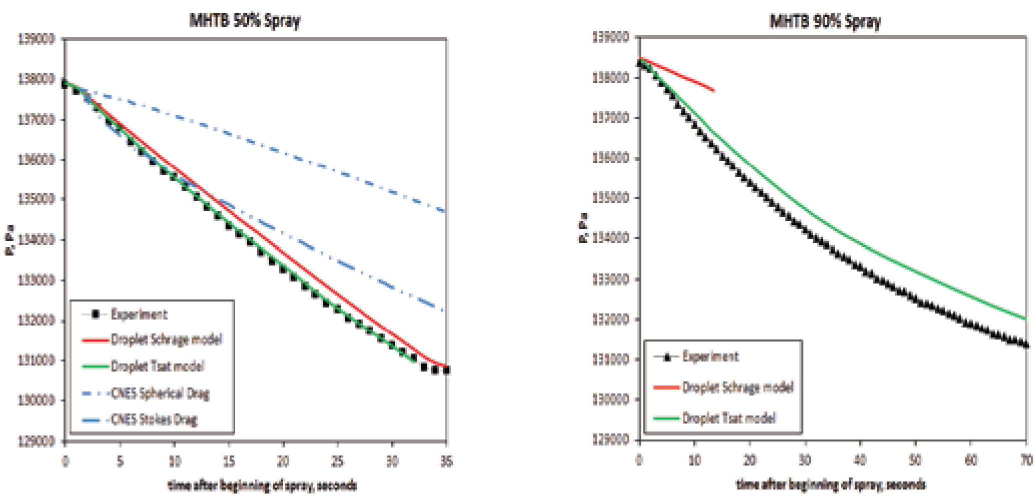
# CFD Results: Spray – Improved T-Sat Droplet Mass Transfer Model




An improved droplet Tsat phase change mass transfer model was developed. The new model improved the predictions for both 50% and 90% fill levels with out using accommodation coefficients

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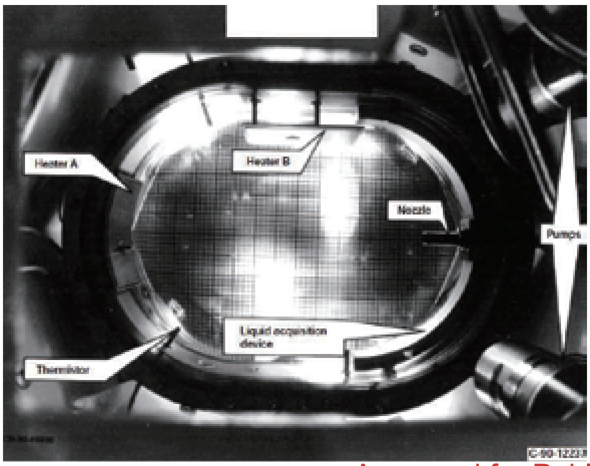
# CFD Simulations of Tank Pressure Control Experiment STS-43 Axial Jet Mixing (fluid dynamics only)



## Shuttle Tank Pressure Control Experiments (TPCE)

- NASA-CR-191012 (1993), NASA-TP-3564 (1996), AIAA-1997-2816
- 25.4 cm (10 in) diameter by 35.56 cm (14 in) long cylindrical tank with hemispherical domes was constructed of transparent acrylic plastic
- Filled with Freon-113: 83% liquid fill for Shuttles flights 1 and 2. 39% liquid fill for 3rd Shuttle flight.




- Small amount of noncondensable gas (helium, water vapor, and air) was present
- Straight-tube jet nozzle (1.016 cm ID). Jet Temperature (T7) was measured.
- “Top” (Heater A) and Sidewall (Heater B) heaters are inside tank close to tank wall
- Pressure, Fluid and Heater Temperature & flow rates measured. Video recorded.

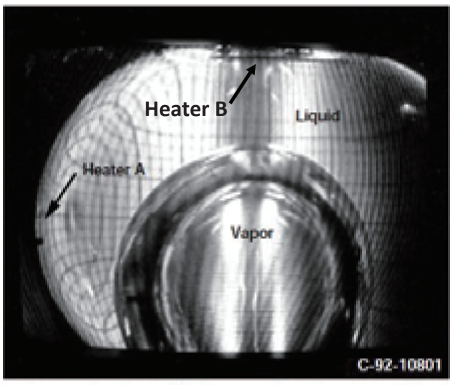



Figure 14.—Actual liquid-vapor configuration during flight experiment.

## TPCE Tank Dimensions

Jet nozzle: OD = 1.27 cm ; ID = 1.016 cm

Tank Diameter = 25.4 cm

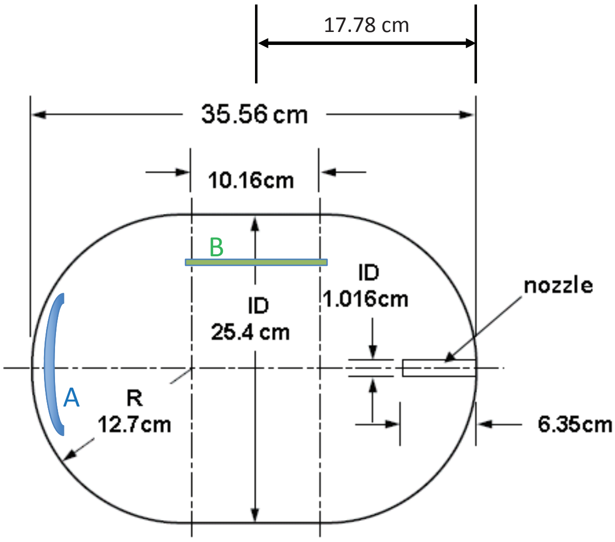
Heater A: gap G ~ 0.3915 cm
thickness = 0.417 cm
12.1 cm radius of curvature
(assumed to center of heater)
12.7 = 12.1 + (0.417/2) + G

Heater B: gap G ~ 2.5 cm
thickness = 0.417 cm
Flat

LAD: wall gap = 0.5588 cm

Heaters and LAD are not drawn to scale

Mixer pumps are outside of tank




**Cylindrical tank with hemispherical domes and jet nozzle along centerline.**
**Inner tank height/diameter = 35.56/24.5 = 1.45.**
**Inner tank diameter/jet nozzle ID = 25.4/1.016 = 25**

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## TPCE Visual Results

### Characterizing Jet Mixing during TPCE

**Nonpenetrating**
Jet does not penetrate through ullage

**Asymmetric**
Jet forces ullage to one side of tank

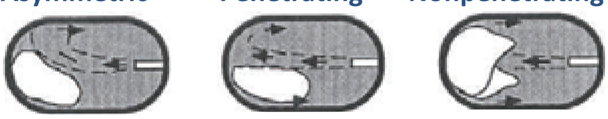
**Penetrating**
Jet completely penetrates ullage and flows back along tank walls

(Ullage breakup may fluctuate between symmetric and asymmetric distribution)

| Run Number | Flow Rate (l/min) | Weber Number | Flow Pattern |
|---|---|---|---|
| 25 | 0.38 | 0.29 | Nonpen. |
| 32 | 0.38 | 0.30 | Nonpen. |
| 3 | 0.54 | 0.59 | Nonpen. |
| 11 | 0.59 | 0.71 | Nonpen. |
| 16 | 0.60 | 0.72 | Nonpen. |
| 8 | 0.60 | 0.73 | Nonpen. |
| 20 | 0.60 | 0.73 | Nonpen. |
| 23 | 0.62 | 0.77 | Nonpen. |
| 33 | 0.64 | 0.82 | Nonpen. |
| 27 | 0.80 | 1.29 | Nonpen. |
| 31 | 0.84 | 1.44 | Nonpen. |
| 29 | 1.24 | 3.10 | Asym. |
| 26 | 1.24 | 3.11 | Asym. |
| 4 | 1.53 | 4.73 | Asym. |
| 7 | 1.53 | 4,74 | Asym. |
| 15 | 1.53 | 4.74 | Asym. |
| 12 | 1.54 | 4.78 | Penetr. |
| 34 | 1.54 | 4.79 | Asym. |
| 24 | 1.57 | 4.96 | Penetr. |
| 19 | 1.58 | 5.06 | Penetr. |
| 28 | 1.71 | 5.90 | Asym. |
| 30 | 1.77 | 6.30 | Penetr. |
| 2 | 2.68 | 14.51 | Penetr. |
| 5 | 2.72 | 14.91 | Penetr. |
| 10 | 2.74 | 15.16 | Penetr. |
| 13 | 2.78 | 15.55 | Penetr. |
| 17 | 2.78 | 15.62 | Penetr. |
| 36 | 2.82 | 16.08 | Penetr. |
| 22 | 2.84 | 16.22 | Penetr. |
| 37 | 3.34 | 22.48 | Penetr. |
| 38 | 3.35 | 22.64 | Penetr. |

*Figure 43: Flow Pattern versus Flow Rate and $We_j$*

**Asymmetric** **Penetrating** **Nonpenetrating**



$3.1 < We_j < 4.8$ $6.3 < We_j$ $We_j < 1.44$

Figure from
"Tank Pressure Control in Low Gravity by Jet Mixing", Benz, M, NASA CR 191012, March 1993

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## CFD simulations of TPCE axial jet mixing

- Simulate 3 TPCE axial jet mixing test runs (low $We_j$, medium $We_j$,, high $We_j$,) without heat transfer and without mass transfer to assess whether we can capture large scale fluid dynamic phenomena (jet penetration or geyser; asymmetric versus symmetric penetration)
- Simulations in 2016 will include heat and mass transfer
- Used FLOW-3D and ANSYS Fluent with Volume of Fluid (VOF) for treating 2-phase flow
- Selected TPCE Test Runs with good video quality and reasonably well-defined initial ullage location
- STS-43 Test Runs simulated (Start of mixing period only; 4 minutes video = 240 seconds)
  - STS-43 Test Run 11 (WeJ = 0.708 → small stable geyser formed; Heater A; Right camera)
  - STS-43 Test Run 15 (WeJ = 4.742 → asymmetric penetration; Heater A; Right camera)
  - STS-43 Test Run 13 (WeJ = 15.55 → symmetric penetration; Heater A; Right camera)
  - STS-43 Test Run 4 (WeJ = 4.74, ullage bubble initially closer to jet nozzle versus Test Run 15, Left camera)

$We_j$ = Weber number of jet at the impingement point of the ullage bubble

$R_J$ = Jet Nozzle exit radius
$V_J$ = Jet Nozzle exit speed
$D_{Ji}$ = Diameter of Jet at Interface based on
0.22 $R_J$ + 0.38 (axial distance nozzle exit to interface)

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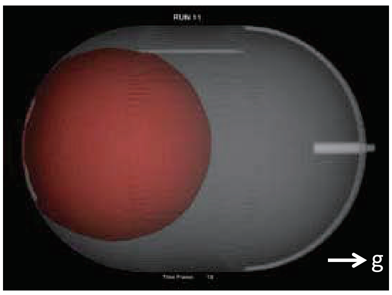
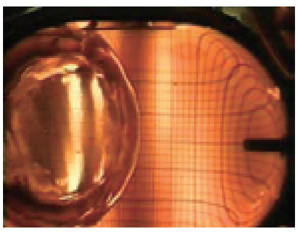
## TPCE STS-43 CFD Initial Conditions (Run 11 shown)

FLOW-3D




TPCE



NOTE: The FLOW-3D image is rotated "more" about the jet axis than the TPCE image.

CFD simulations start with the initial interface shape and location shown, and:
T = uniform = 296 K
P = uniform = 41.164 kPa
Velocity = 0 everywhere
We are not simulating the heating period – that will occur in FY16 when we include heat/mass transfer

CFD simulation is run for 20 seconds with the jet OFF to verify/allow the interface shape and position establish an equilibrium position before turning on the jet.

CFD simulations use a constant acceleration magnitude (1e-6 g) and direction (see figure).

All walls/solid-surfaces are adiabatic.

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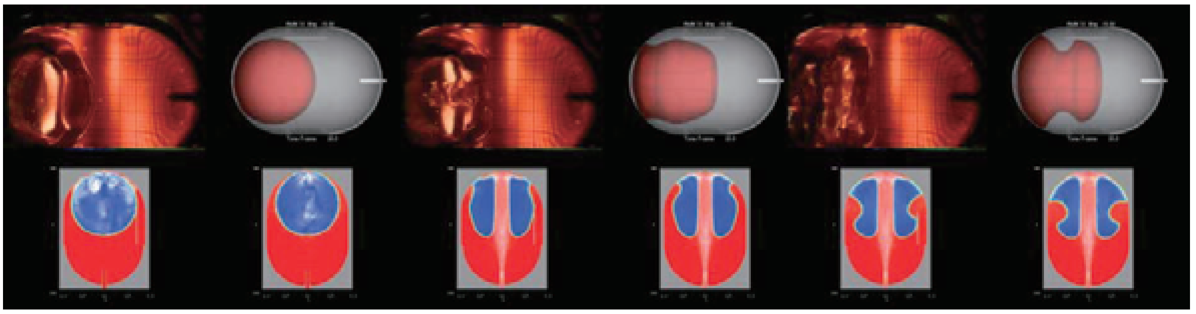
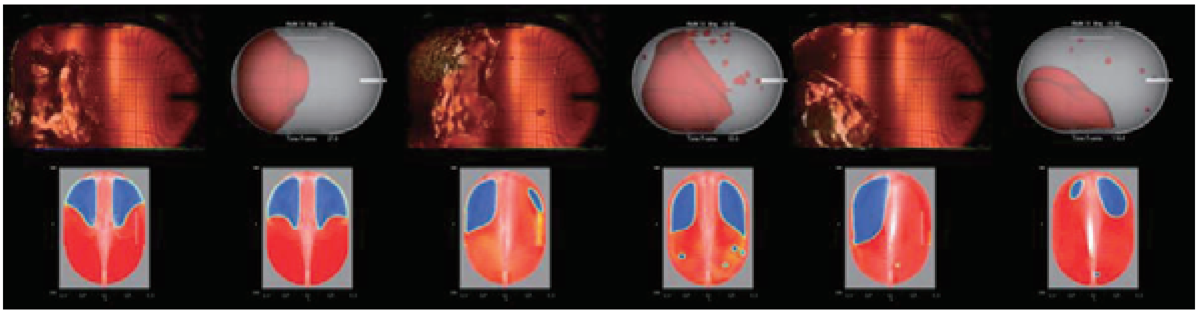
## Experiment & FLOW-3D: Test Run 13　$We_j$ – 15.5　Penetrating



t= 20s　t= 23s　t= 25s



t= 27 s　t= 53 s　t= 116 s

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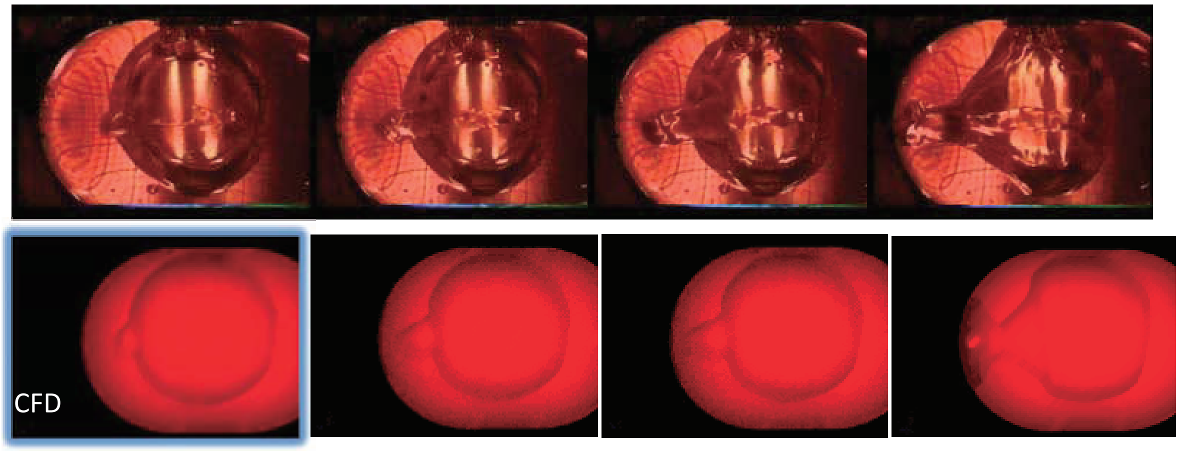
## Test Run 4　($We_j$=4.74 = same as Test Run 15)

- Comparison of CFD simulation to experimental ullage protuberance
- Ullage bubble is approximately in tank center before Jet is turned ON
- Same Jet Weber Number as Test Run 15, but different initial ullage location




t=1.25 s　t=1.45s　t=1.55s　t=2.6s

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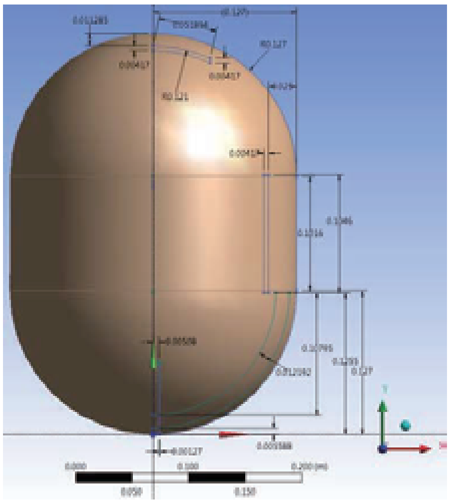
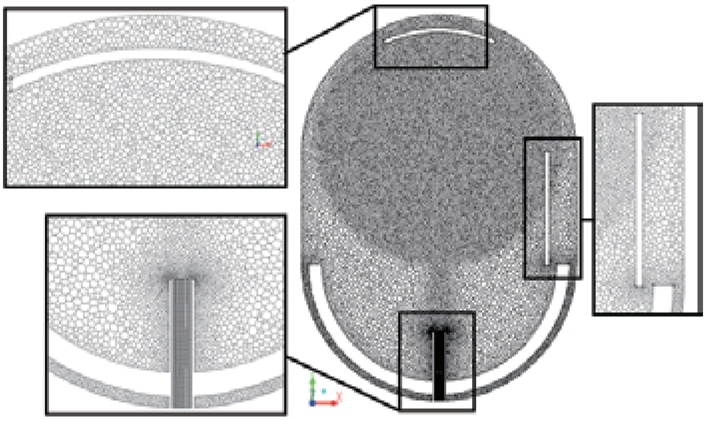
## Geometry and Mesh for Fluent Simulations

**Full 3D Geometry**



TPCE tank geometry and dimensions



Computational mesh (1,505,726 polyhedral cells)

Gap between LAD and Wall resolved

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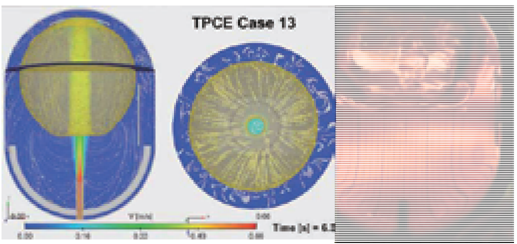
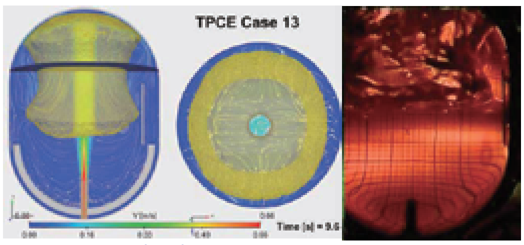
## TPCE STS-43 Test Run 13

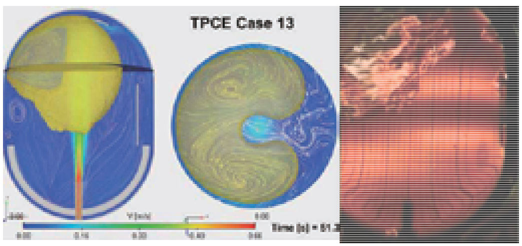
**TCPE Computational (FLUENT) & Experimental Time Sequence Comparison of Axial Jet Ullage Penetration for Test Run 13: We = 15.55, $V_{jet}$ = 0.57 m/s**



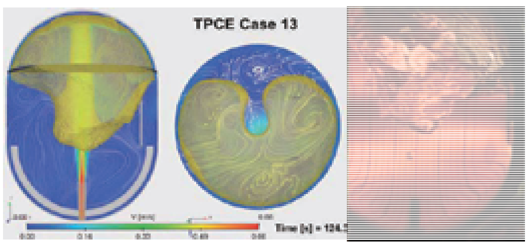

**Sequence A (6.3 s):** tubular flow penetrating the ullage along the central axis




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




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




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

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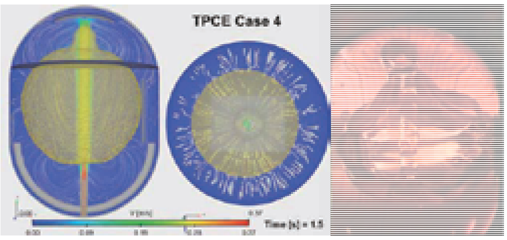
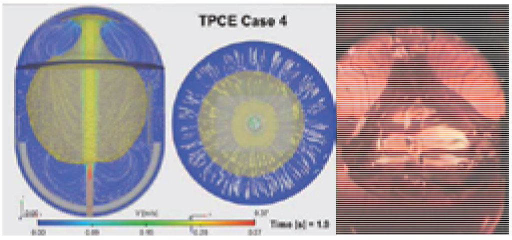
# TPCE STS-43 Test Run 4

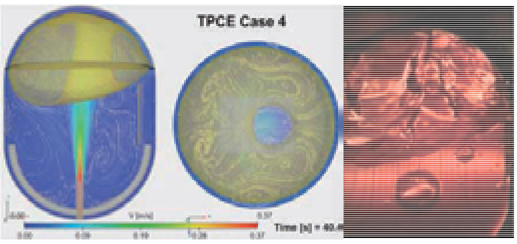
## TCPE Computational (FLUENT) & Experimental Time Sequence Comparison of Axial Jet Ullage Penetration




Sequence A (1.5 s): tubular flow penetrating the ullage along the central axis exhibiting necking at the top of ullage.




Sequence B (1.9 s): spreading of the back flow over the ullage and widening of the top neck to form a cone




Sequence C (40.4 s): compression of the ullage against top wall, thickening of the tubular jet penetration flow as it moves to the right creating asymmetry

| Test Run | Weber Number | Flow rate, l/min | Jet Velocity, m/s |
|---|---|---|---|
| 4 | 4.74 | 1.53 | 0.32 |

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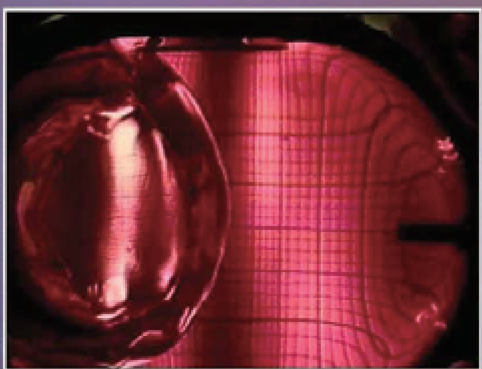
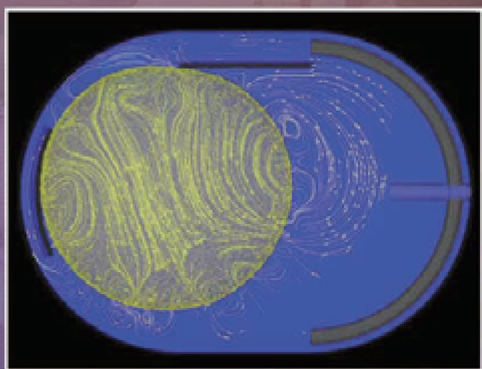
## Tank Pressure Control Experiment (TPCE) Small Scale, Simulant Fluid Microgravity: STS-43 1991



TPCE: Experiment



NASA GRC CFD: Simulation

Case 11 Weber number = 0.71 Jet Velocity = 0.12 m/s

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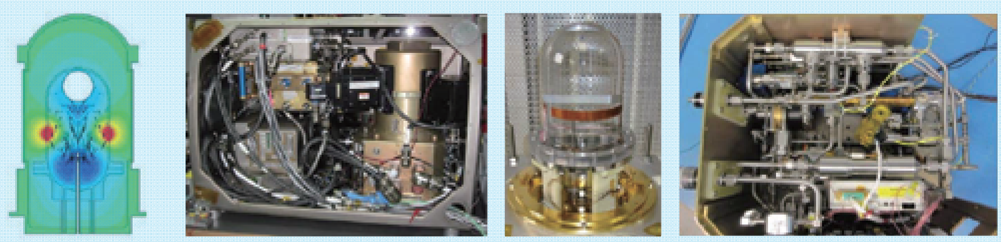
# *Zero-Boil-Off Tank (ZBOT) Experiments*

***Dr. Mohammed Kassemi, Principle Investigator***



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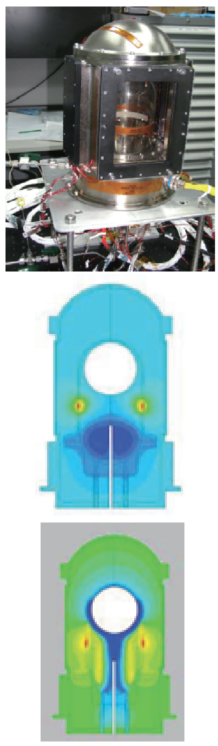
## Zero-Boil-Off Tank (ZBOT) Experiments

- A small-scale *simulant*-fluid experimental platform to be accommodated in the Microgravity Science Glovebox (MSG) unit aboard the ISS.
- 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



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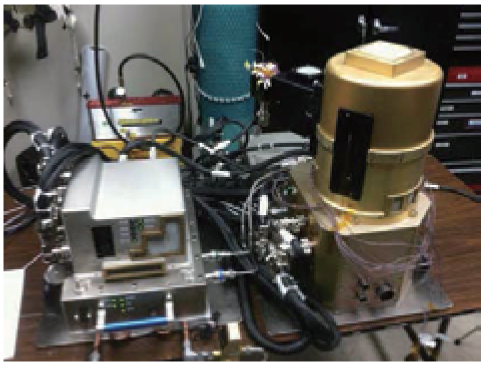
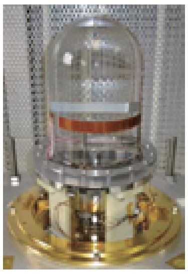
## ZBOT Series of Hierarchical Experiments

- **ZBOT Science Review Panel** composed of six CFM experts from academia, aerospace industry, and NASA laboratories strongly endorsed the objectives of the experiment but recommended that they should be achieved in an incremental manner through a series of experiments with increasing complexity.
  - ✓ **ZBOT-1: (Launch 8/2016; Ops. 12/2016)**
    - Pressurization, pressure reduction by Jet Mixing & destratification
    - Model development and validation
  - ➢ **ZBOT-2:**
    - Noncondensable effects on pressurization and pressure control
  - ➢ **ZBOT-3:**
    - Different active cooling mechanism: Droplet Spray Bar; Axial Jet Mixing; Broad Area Cooling
    - Droplet phase change & transport in microgravity





- The follow-on experiments will benefit greatly from heritage developed by ZBOT-1

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## ZBOT-1: Tank Pressurization & Mixing Destratification (Measurements & Data)

| 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 |

68 pressurization, jet mixing, and destratification tests will be performed at 3 fill levels with and without Particle Imaging Velocimetery (PIV)

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# Validation with Ground-Based Results

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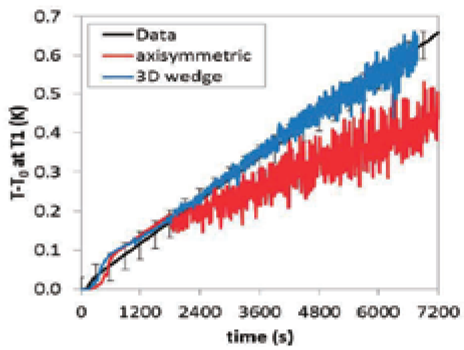
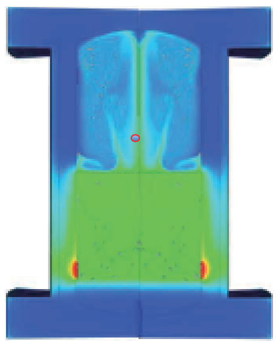
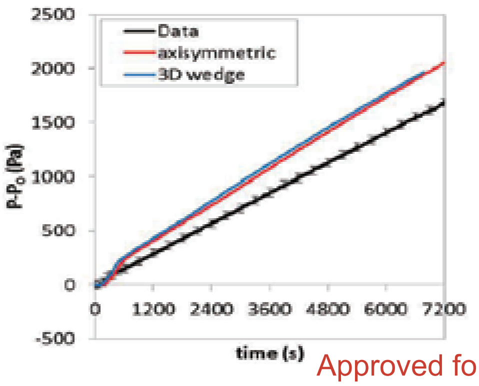
## *1G* Self-Pressurization: *Model Prediction vs Experiment*

Air at 20 Torr

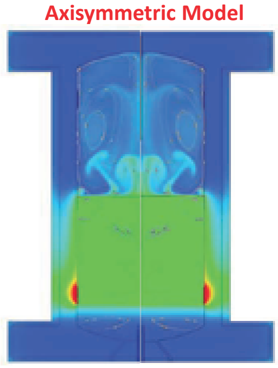



3D Model






Axisymmetric Model



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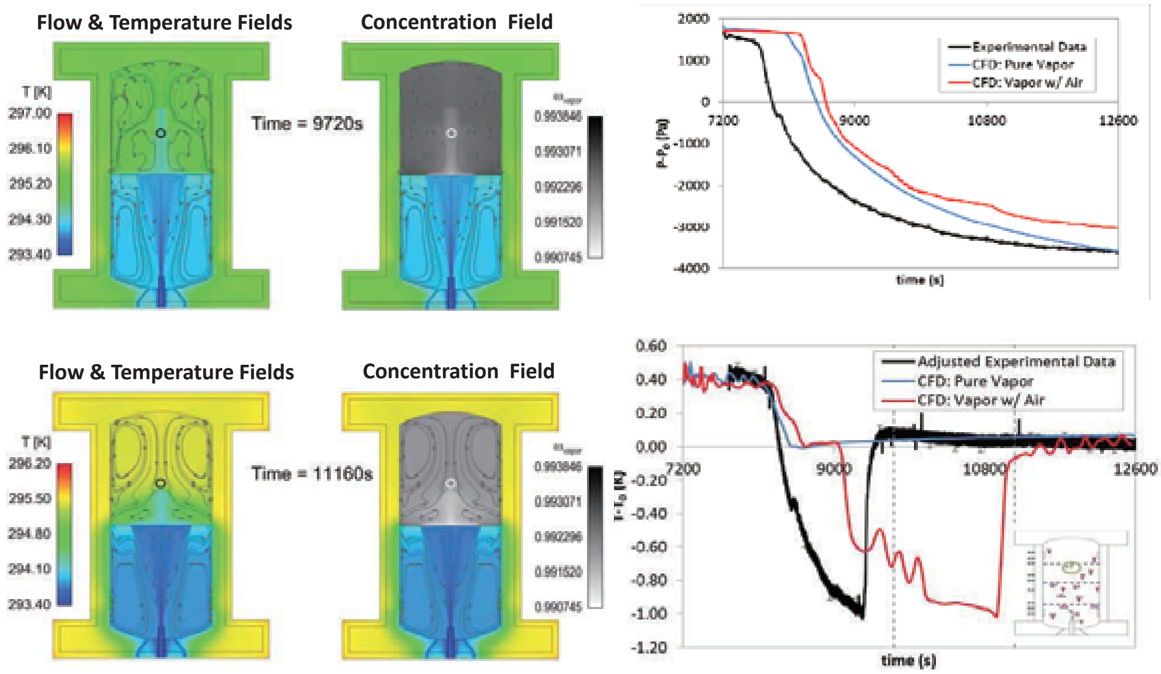
## *1G* Pressure Control Simulations

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## Microgravity Predictions

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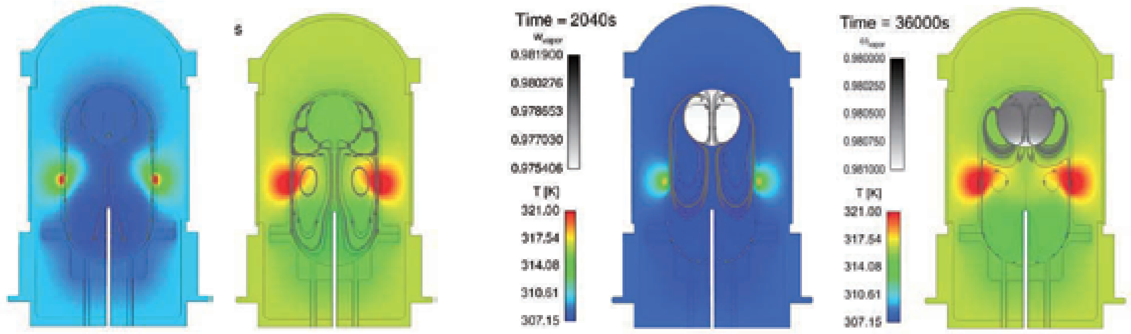
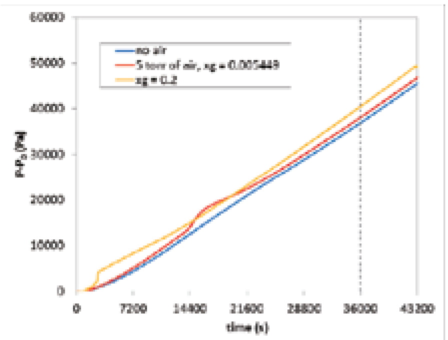
## ZBOT-1 Simulations- Microgravity Pressurization

No air

With Air ($X_{air}$ = 0.2)




- In Microgravity, the ullage is spherical, the interface is curved *and the **tank wall is all wetted***.
- A prominent laminar natural convective torroidal flow ensues mainly near the heater and interface.
- The Microgravity thermal stratification pattern and its magnitude is significantly different from the 1G case.
- Ullage pressure still rises due to wall heating from the top.

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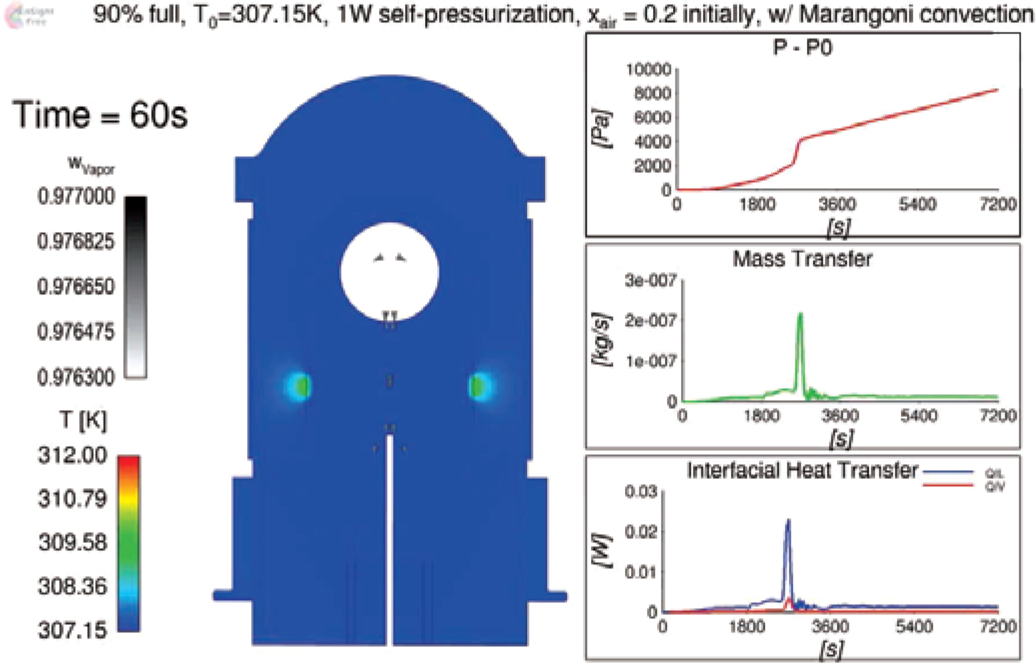
## ZBOT Self Pressurization (Flight)

90% full, $T_0$=307.15K, 1W self-pressurization, $x_{air}$ = 0.2 initially, w/ Marangoni convection

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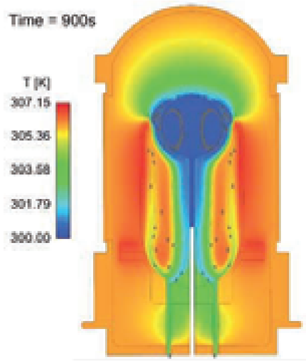
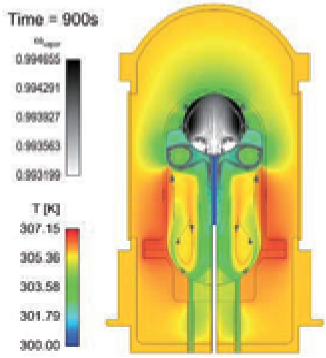
## ZBOT Simulations: Micro-G Pressure Control

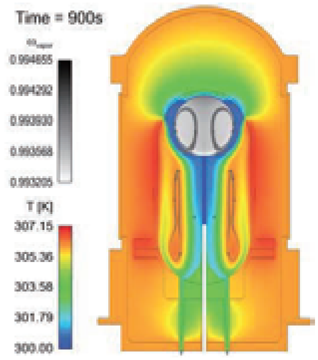
$T_0$ = 307.15K, 5 cm/s 300K jet, no air, w/ Marangoni convection

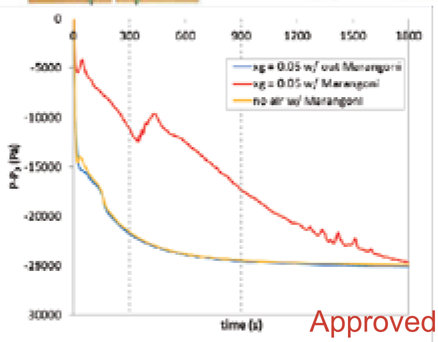



$T_0$ = 307.15K, 5 cm/s 300K jet, $x_{air}$ = 0.05 initially, w/ Marangoni convection




$T_0$ = 307.15K, 5 cm/s 300K jet, $x_{air}$ = 0.05 initially, w/o Marangoni convection




- Test Tank is enclosed in a vacuum jacket
- Tank is initially at an elevated uniform temperatures with strip-heater off.
- A forced sub-cooled jet at 5cm/sec is used for pressure control

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## Summary

- NASA is pursuing advancement of computational simulations for cryogenic propellant management systems. Areas of interest include:
  - Pressurization (with and without non-condensible in the ullage)
  - Destratification (Active mixing)
  - Transfer line and tank chilldown
  - Tank filling and draining
- Tools for simulating cryogenic fluid in propellant tanks range from multi-node design and trade-study codes to full 3D CFD.
- Validated Analysis Tools will reduce the development cost and risk for future NASA Exploration missions employing in-space cryogenic storage and transfer systems.

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