Zero Boil-Off Tank (ZBOT) Experiment

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ZBOT Project Team

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Science Background

NASA’s Cryogenic Fluid Management Challenges

- Reliable cryogenic storage for use in propellant systems is essential to meeting NASA’s future exploration goals.
- Heat leaks from surroundings lead to cryogen boil-off and excessive tank pressures.
- Tank is vented to reduce pressure, but also results in loss of cryogenic fluid.
- Predicting boil-off and self-pressurization rates is important to identify both active and passive techniques to minimize these losses.

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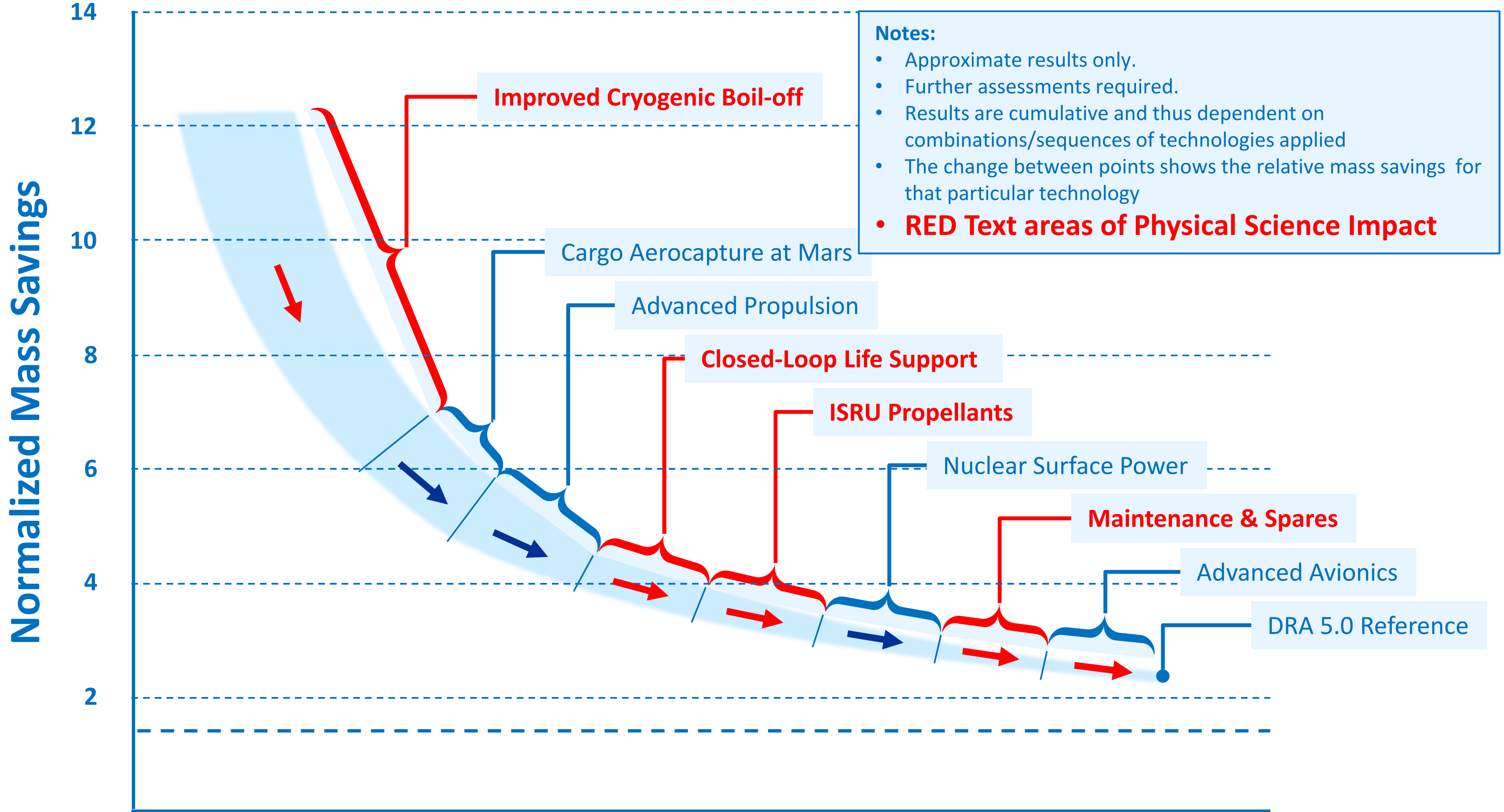
Significance of Cryogenic Research: Mars Mission Example



- Physical sciences research on ISS provides the knowledge base for designing systems, ISS provides a platform to validate technologies for inclusion in flagship missions.

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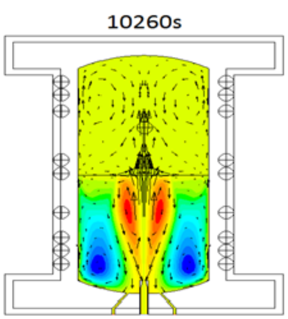
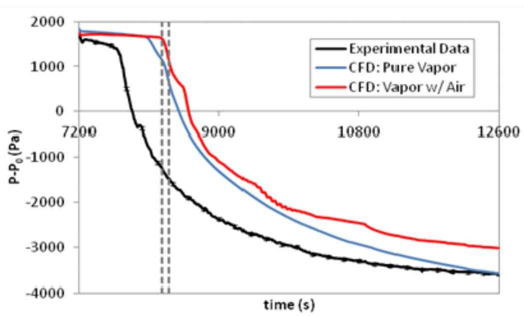
ZBOT Science Objectives

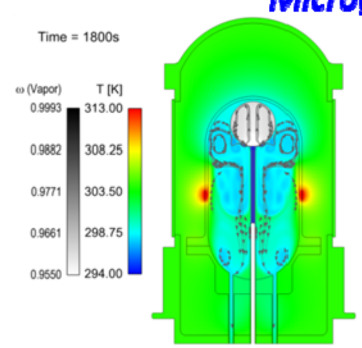
1. Develop a small-scale simulant-fluid experiment for both preliminary ground-based testing and subsequent ISS flight experiments to obtain valuable microgravity empirical data for tank pressure control design and archival science data for model validation.
2. Build a science base for future space storage tank engineering efforts by elucidating the roles of the various interacting transport and phase change phenomena that impact tank pressurization and pressure control in variable gravity through systematic 1g and microgravity scientific investigation.
3. Develop, validate, and verify two-phase CFD models for tank pressure control that can be used to aid the future scale-up tank design.
4. Demonstrate the feasibility of Zero-Boil-Off (ZBO) pressure control schemes for microgravity and variable gravity applications by examining the effect of forced mixing of the bulk liquid on destratification and pressure reduction in a ventless Dewar.

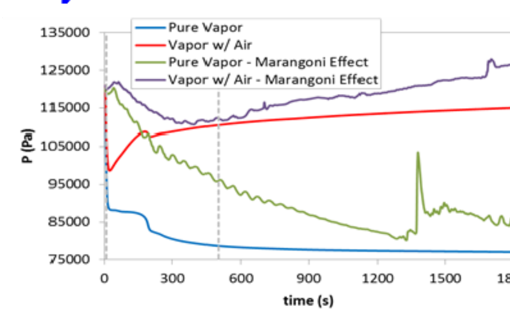
1G Jet-Mixing Pressure Control: Simulation & Experimental Validation





Different Trends Predicted for *Microgravity* Pressure Control





ZBOT Measurement Approach

- Transparent test tank accommodates the simulant fluid (perfluoro-*normal*-pentane - C_5F_{12}), mixing nozzle, heaters, and sensors.
- Thermal conditions of the tank and fluid are controlled: The test tank is isolated inside a vacuum jacket by insulating supports.
- Resistance Temperature Detectors (RTDs) and pressure transducers provide temperatures and pressures to assess the thermodynamic state of the test fluid.
- Fluid Support Unit provides flow and fine thermal conditioning of fluid.
- Fluid Reservoir provides fluid storage and the ability to change the fill level in the tank per the test matrix.

ZBOT in the MSG Engineering Unit
(at NASA MSFC)

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Camera Package Mounting Location

Data Acquisition and Control Unit (DACU)

SAMS Head Mounting Location

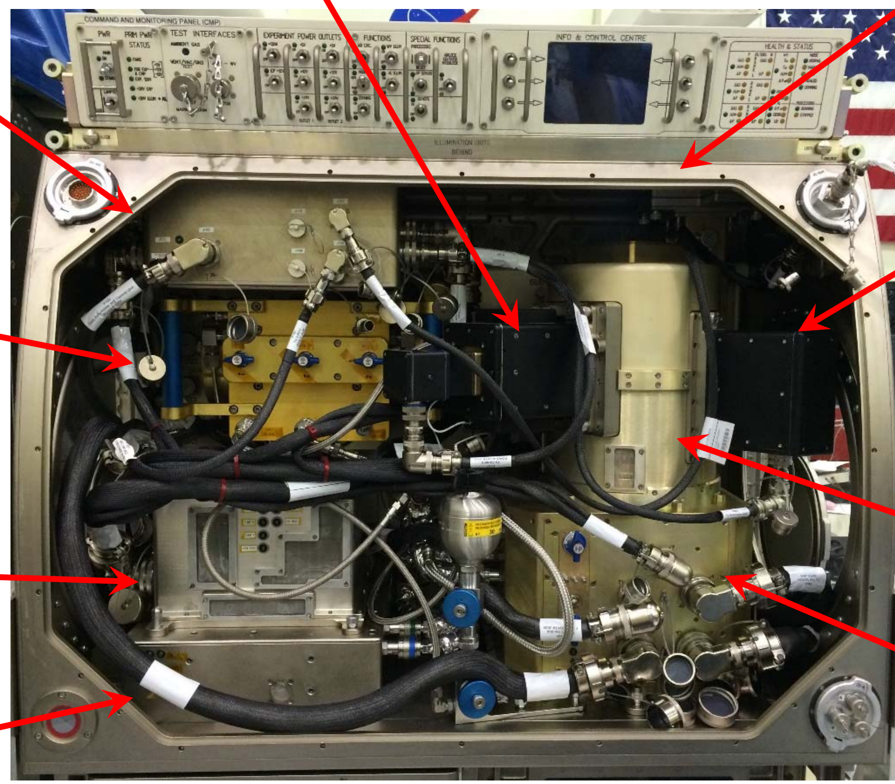
Illumination Package

Fluid Reservoir

25.1”

Thermal Control Unit (TCU)

Cold Plate Package (CPP)



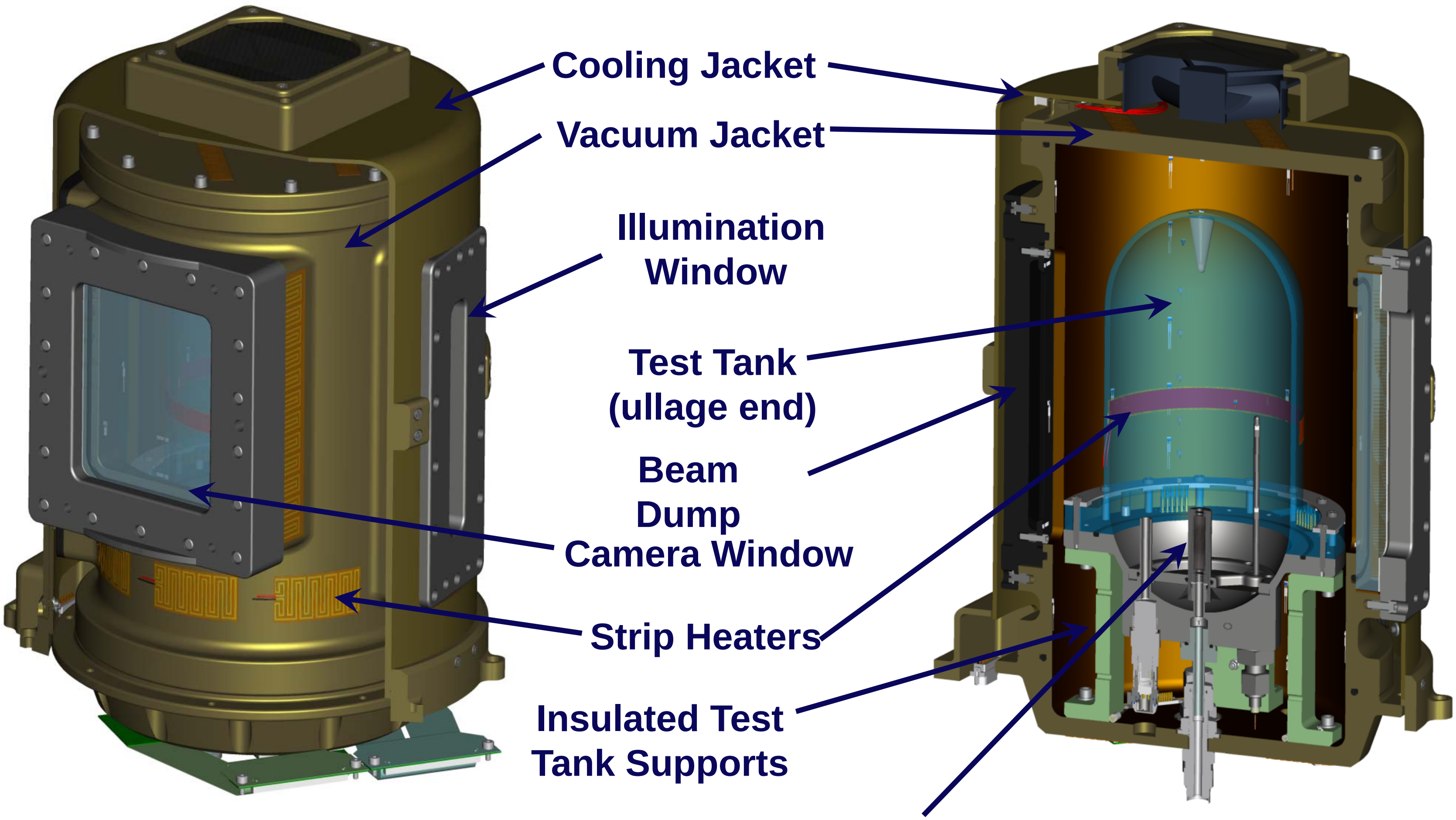
Test Section (14.0”W x 22.5”H x 14.8”D)

Fluid Support Unit (FSU)

35.7”

Not Shown: Particle Injector and MSG Window.

ZBOT Test Section



Tank Volume: 0.83 L Tank Diameter: 10 cm Tank Height : 20 cm.

Ability to have localized and global heating.

ZBOT Operational Overview

ZBOT Operational Scheme:

1. Adjust tank fill level as necessary.
2. Thoroughly mix tank contents to achieve initial uniform temperature distribution in liquid.
3. Heat tank
    1. Use either tank wall heaters or radiate from vacuum jacket.
    2. Measure pressure and temperature rise.
4. Inject measured flow of controlled liquid temperature into tank.
    1. Measure pressure and temperature changes.
    2. Visualize jet penetration into ullage bubble.
5. Repeat as necessary (66 test points).

Technology Demonstration of Particle Imaging Velocimetry:

6. Conduct tests after completing test matrix at 90% fill level.
7. Inject particles as necessary.
8. Repeat steps 2 – 5 but visualize particle flow patterns in steps 3 & 4 (32 test points).

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Importance and Reason for ISS

Duration of microgravity test conditions:

- Permits well-defined initial conditions to be established for each test run.
  - Uniform Temperature
  - Quiescent
- Lack of buoyancy-driven convection establishes a fluid stratification that is significantly different than in a terrestrial environment.
- Significant curvature of ullage bubble in reduced gravity cannot be established in normal gravity environment.
- Bubble position within tank can be influenced by both liquid jet and Marangoni flows.

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Key Questions and Impact on Advancing the Field

- How much natural mixing (buoyancy vs. surface tension-driven) will take place in a given tank during operation at various gravitational levels?
- How much forced mixing is needed to thermally de-stratify the tanks without active cooling?
- Under what conditions will it be necessary to augment the thermal destratification through active cooling?
- How effectively do mixing-only and/or mixing-with-active-cooling decrease the pressure reduction times?

Need: reliable engineering correlations for mixing, destratification, and pressure reduction times as functions of relevant tank parameters such as heat leak rates, mixing flow rates, and fill levels

Application: sizing of the pumps, determining forced mixing modes, possible placement of flow control structures, and sizing and implementation of the active cooling mechanisms (TVS, Cryocooler, etc.)

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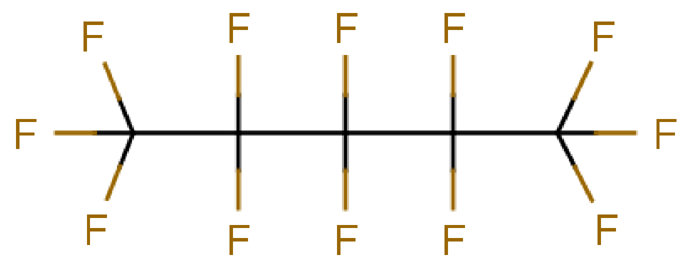
Benefits/Spin-off Applications

- Space:
  - Reduced propellant launch mass (cost) and decreased risks for future space missions by aiding the development of dynamic pressure control schemes for long-term storage of cryogenic fluids.
  - Increased design reliability by providing archival data for benchmarking and improving computational fluid dynamic models used by the cryogenic fluid management community and aerospace companies for future tank designs.
- Earth Benefit
  - Advances the state-of-the-art knowledge in cryogenic fluid management and two-phase flow and heat transfer.

Backup Charts

ZBOT Test Fluid

- Perfluoro-n-Pentane (PnP, or C_5F_{12})
- High purity (99.7% straight-chained n-isomer).
- Non-flammable, non-toxic, refrigerant/cleaning fluid.
- Physical properties
  - Boiling Point = 29°C @ 1 atm
  - Vapor Pressure = 12.5 psia @ 25°C
  - Liquid Density ~ 1.6 g/cm^3
  - Liquid Viscosity ~ 0.6 cP
  - Surface Tension ~ 9 dynes/cm
  - ΔH_{vap} ~ 90J/g
  - Liquid Specific Heat ~ 1.09 J/g°C
  - Liquid Thermal Conductivity ~ 0.056 W/m°C
- Benefits:
  - Relatively volatile at room temperature
  - Tox 0 – Approved by JSC toxicology and MSFC ECLSS groups



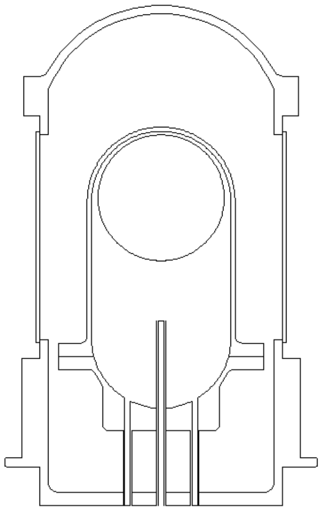
PnP n-Isomer (Straight Chained) Chemical Structure

ZBOT-1 Measurements & Data

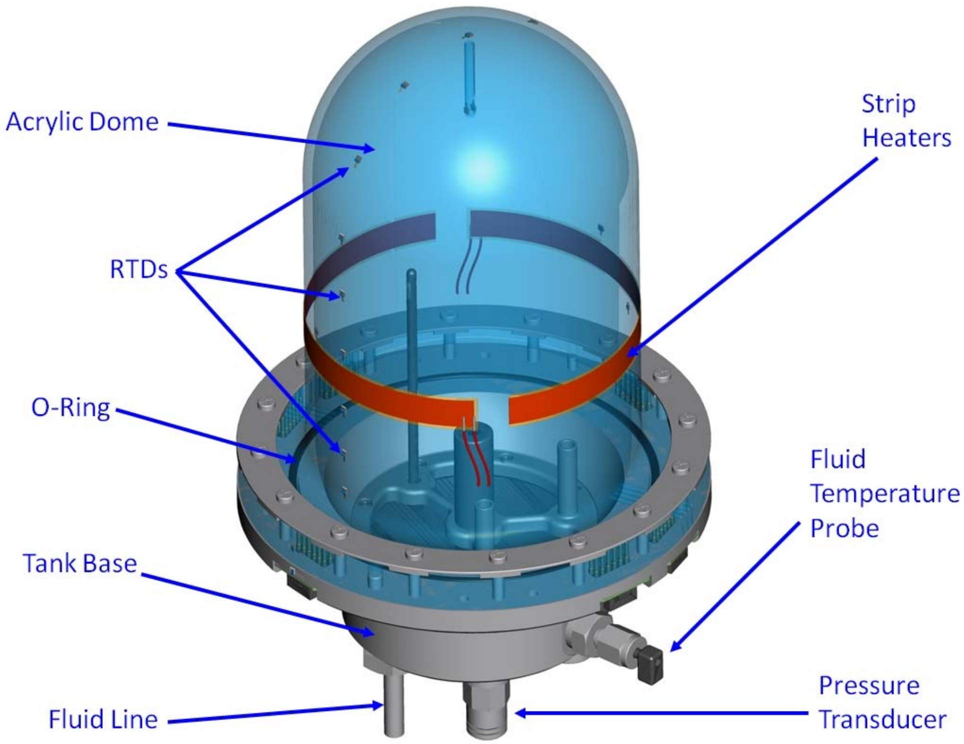
Type of Test	Method & Mode
Pressurization	Heater Strip
	Vacuum Jacket Heating
	Heater and Vacuum Jacket
Mixing Only	Uniform Temperature
	After Self-Pressurization
Subcooled Mixing	Uniform Temperature
	After Self-Pressurization

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

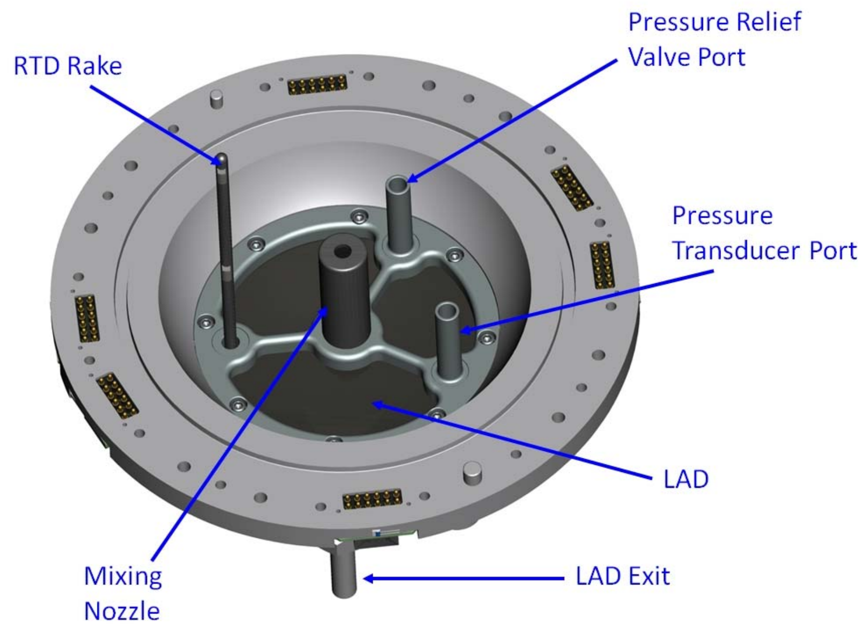
Input Variables (Tolerances)
Heater Power (w/ in 5 mW RMS)
Vacuum Jacket Offset (+/- 0.2°C)
Fill Level (70% +/- 3%, 80% +/- 3%, 90% -3%)
Jet Temperature (+/- 0.25°C)
Jet Velocity/Flow rate (10% of reading)



Test Section – Test Tank

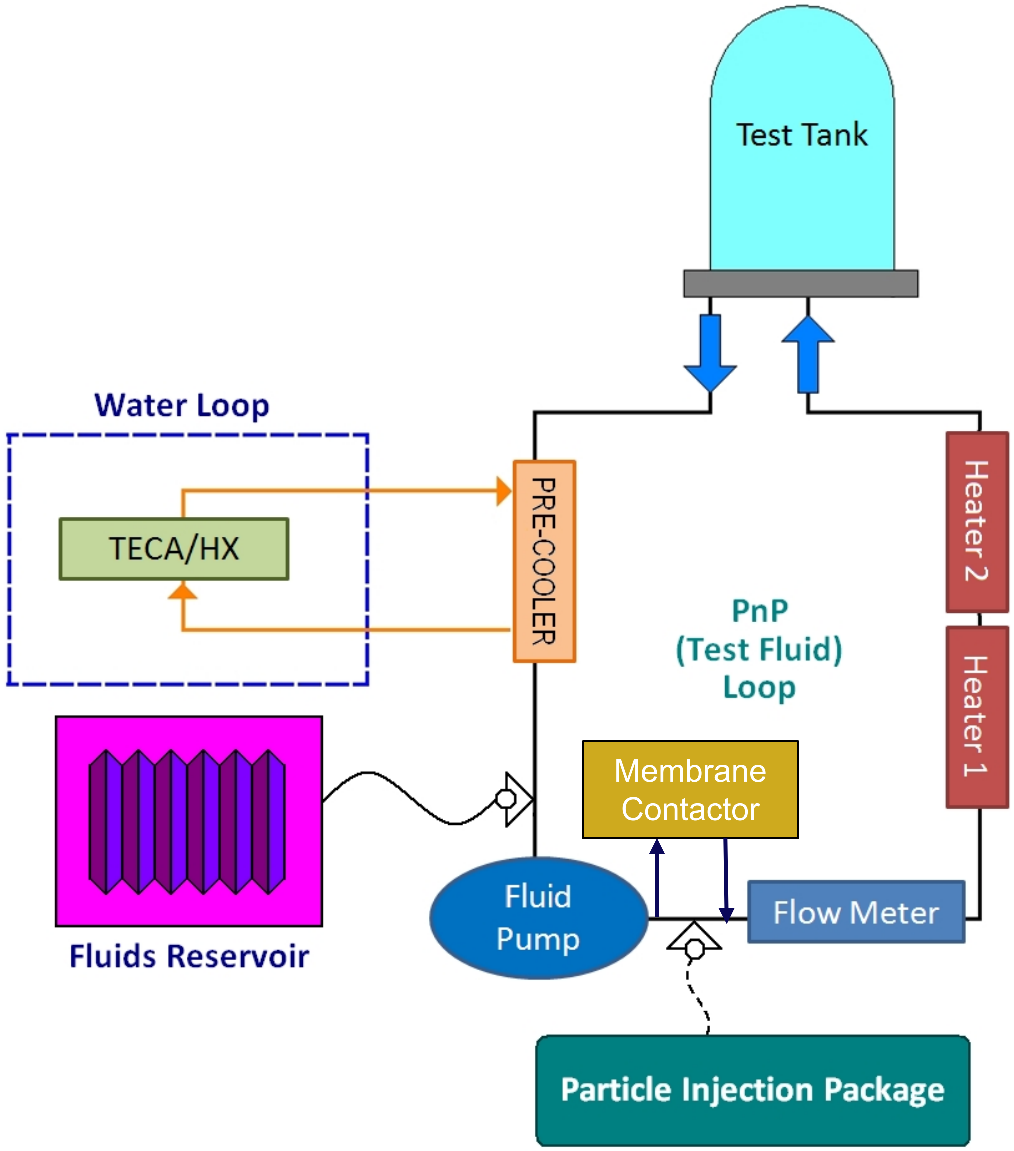


PMMA (Acrylic) Test Tank Dome



Stainless Steel Test Tank Base

ZBOT Simplified Fluids Schematic



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ZBOT Flight Fluids System Schematic