The Zero Boil-Off Tank (ZBOT) Experiment Role in Development of Cryogenic Fluid Storage and Transfer Technologies

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### ZBOT Project Team

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**ENGINEERING**
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**Team Members:**
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- Darryl Seeley – Quality Assurance, ZIN
Cryogenic Storage & Transfer are enabling propulsion technologies in the direct path of nearly all future human or robotic missions.

- It is identified by NASA as an area with greatest potential for cost saving.
- This proposal aims at resolving fundamental scientific issues behind the engineering development of the storage tanks.
- We propose to use the ISS lab to generate & collect archival scientific data:
  - raise our current state-of-the-art understanding of transport and phase change issues affecting the storage tank cryogenic fluid management (CFM)
  - develop and validate state-of-the-art CFD models to innovate, optimize, and advance the future engineering designs.
NASA is undertaking a demonstration mission to advance cryogenic propellant storage and transfer technologies that will enable exploration beyond Low-Earth Orbit.

- **Passive Storage Demo**
  - Check-out: 2 weeks
  - 1 month

- **Active Storage Demo**
  - 5 months
  - 6 months

- **Controlled Re-Entry**

**Launch 2016**

- Demonstrate long duration storage
- Demonstrate in-space transfer
- Demonstrate in-space, accurate gauging
Broad Scientific Goals of ZBOT

• Perform hand-in-hand experimentation, theoretical analysis, and computational modeling to:

1. Gain a fundamental understanding of the phase change and transport phenomena associated with tank pressurization and pressure control
2. Determine the time constants associated with pressurization, mixing, destratification, and pressure reduction for different gravitational environments
3. Determine the effects of noncondensables on evaporation and condensation and transport phenomena
4. Delineate the different microgravity transport/phase change mechanisms associated with different mixing/cooling strategies
5. Investigate the nature of microgravity superheating and its effect on boil-off
6. Validate and verify a state-of-the-art two-phase CFD model for cryogenic storage

• Produce archival data and simulations that will not only benefit the cryogenic storage tank design but a multitude of other two-phase flow operations and processes in space
ZBOT-1 Engineering Questions: Pressurization & Pressure Control

- How much natural mixing 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.)
Important Experimental Components & Science Requirements

ZBOT Components
- ventless Dewar(s)
- temp-controlled shield
- fluid support unit
- axial mixing jet
- longitudinal spray bar
- noncondensable gas injection
- Liquid Acquisition Devices (LADs)

ZBOT Requirements:
- transparent Dewar & fluid
- tightly controlled thermal & flow BCs
- accurate & local temperature measurement
- in-flight fluid degassing
- accurate determination of ullage pressure and gaseous concentration
- whole-field visualization of interface, flow, and velocimetry using PIV.

Main CPST Elements:
- Broad Area Cooling (BAC)
- active internal cooling
- dynamic mixing
- noncondensable effects
- liquid transfer
- mass gauging
- LAD operations
**NRC Decadal Report:**

- “1G empirically-based predictive methods in the design of the future multiphase technologies are of limited use”
- “a new predictive capability and design methodology needs to be adopted that relies in particular on physically-based multiphase models that quantify accurately the effects of gravity.”
- “to be effective, such models must necessarily be assessed against, appropriate small scale reduced-g data, and they must be capable of accurately scaling-up these data to the large multiphase systems for NASA’s future human exploration missions.”

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**CPST:** Validate the Technology - Demonstrates performance of the engineering components: cryocoolers, pump, radiation shield

- Controllable BCs -accurate measurements
- Flow visualization & velocimetry
- Extensibility Gap in scale and fluid closed by the model

**ISS:**

- CPST extensibility gap: 2 meter ➔ 8 meter
- LH2 ➔ LOX, Methane

**Proposed ISS experiment will be able to bridge the CPST extensibility gaps with future mission applications**
ZBOT-1 will involve both pressurization and pressure reduction tests
  
  • Pressurization tests will be conducted by direct heating of the tank wall
  • Pressure reduction tests will be accomplished through thermal destratification of the bulk liquid by forced jet mixing
  
  • Parametric test runs will investigate the effect of the important system elements of a pressure control strategy on pressurization and pressure control:
    • Wall heat flux (heater)
    • Jet temperature
    • Jet flow rate
    • Tank fill level
  
  • During each test, pressure and temperature are locally measured and the velocity field and ullage location in the liquid are non-intrusively captured
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
- Benefits
  - Has the desired physical properties for science
  - Density matched with DPIV particles
  - Tox 0 – Approved by JSC toxicology and MSFC ECLSS groups

PnP n-Isomer (Straight Chained)
Chemical Structure
Typical Test Approach

1. **Self-Pressurization**
   - Heat for 12 hours max.
   - Heat at 0.5 to 1.0 Watts

2. **Pressure Control via Mixing; Cooling Optional**
   - Mix with \( \frac{dQ}{dT} = 0 \)  \textbf{OR}
   - Sub-cooled mixing used after test to rapidly cool tank
**Boundary Conditions:**

- Add precise heat to fluid using resistive heater strips
- Reduce heat losses through radiation, conduction, and convection
- Circulate temperature-controlled fluid

**Instrumentation:**

- RTDs measure temperature distributions to ±0.1 °C
- Pressure measured to ±0.05 psia
- Fluid velocity fields via Particle Imaging Velocimetry
Test Tank with Vacuum Jacket Removed and Base

Acrylic Dome
RTDs
O-Ring
Tank Base
Fluid Line

Strip Heaters

RTD Rake
Pressure Relief Valve Port
Pressure Transducer Port
LAD
LAD Exit

Fluid Temperature Probe
Pressure Transducer
Mixing Nozzle
Simplified Fluids Schematic

- Test Tank
- Water Loop
- TECA/HX
- PnP (Test Fluid) Loop
- Fluids Reservoir
- Fluid Pump
- Flow Meter
- Particle Injection Package
- PRE-COOLER
- Heater 1
- Heater 2
Hardware Overview

Test Section – Cross Section

- Cooling Jacket
- Vacuum Jacket
- Illumination Window
- Test Tank (ullage end)
- Beam Dump
- Camera Window
- Strip Heaters
- Insulated Test Tank Supports
- Mixing Nozzle
Optical System

- Tank
- Diode Laser
- Beam Dump
- Light Sheet Tilted 12° to increase particle visibility
- Camera Acceptance Cone

Tilted 12° to increase particle visibility
Camera and Illumination Packages Mounted to the Test Section
Zero Boil-Off Tank Experiment-2 (ZBOT-2): Noncondensable Gas Effects

**Objective:**
- Aid the design of NASA’s space-based cryogenic storage systems by investigating the effects of noncondensable gases on tank pressure control.
- Characterize and assess the effects of noncondensables on evaporation and condensation by obtaining microgravity two-phase flow and heat transfer data in a ventless Dewar.
- Gather high quality microgravity data under controlled conditions for validation of storage tank CFD models and development of empirical engineering correlations.

**Relevance/Impact:**
- **Reduce launch mass** (cost) by aiding the development of novel dynamic pressure control schemes for long-term storage of cryogenic fluids.
- **Decrease the risks** of future space missions by clarifying and assessing the impact of noncondensables on storage tank pressure reduction/control.
- **Increase design reliability** by providing archival data for benchmarking and improving CFD models used by the Cryogenic Fluids Management community and the Aerospace Companies for future (ground-tested-only) tank designs.

**Development Approach:**
- Flight phase: **Modify** the ZBOT-1 experimental hardware and diagnostics for non-condensable gas studies; Obtain microgravity data to determine the effect of the noncondensable pressurant on tank pressurization, thermal destratification, and pressure reduction through mixing in microgravity.
- Modeling: **Expand** the ZBOT-1 two-phase CFD model to incorporate the non-condensable gas effects.
- Validation: Validate the noncondensable tank models with microgravity data.
- Scale-up: Use the validated CFD models and empirical microgravity correlations to scale-up the design of the future tanks and dynamic pressure control system.

**ISS Resource Requirements**

<table>
<thead>
<tr>
<th>Resource</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accommodation</td>
<td>Fluids Integrated Rack</td>
</tr>
<tr>
<td>Upmass (kg)</td>
<td>80 - 100 kg</td>
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<tr>
<td>Volume (m³)</td>
<td>0.10 - 0.12 m³</td>
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<tr>
<td>Power (kw)</td>
<td>0.100 kW</td>
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<tr>
<td>Crew Time (hrs)</td>
<td>15 - 20 hrs. total</td>
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<tr>
<td>Launch/Increment</td>
<td>TBD</td>
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</tbody>
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Zero Boil-Off Tank Experiment-3 (ZBOT-3): Active Cooling

Objective:
Aid design of NASA’s cryogenic storage systems by studying different active cooling strategies for future Zero-Boil-Off (ZBO) tank pressure control designs:
- Obtain microgravity flow and heat transfer data to characterize tank thermal destratification and pressure reduction for: (i) sub-cooled jet mixing (ii) spray-bar mixing; and (iii) broad area cooling with intermittent mixing
- Provide high quality microgravity data under controlled conditions for development, validation and verification of tank pressure control models, CFD codes, and empirically-based correlations
- Perform a quantitative comparison among different ZBO active pressure control strategies using microgravity data and model simulations

Relevance/Impact:
- Reduce launch mass (cost) by aiding development of novel active cooling ZBO pressure control schemes for long-term storage of cryogenic fluids
- Reduce the risks of future missions by testing pressure control systems never tested in microgravity and increase design reliability by providing archival data for benchmarking and improving CFD models/codes used by the Cryogenic Fluids Management Community (CFM) and the Aerospace Companies for future (ground-tested-only) tank designs

Development Approach:
- Flight phase: Modify the ZBOT-2 experimental apparatus to accommodate the pressure control components needed for active cooling studies
- Modeling: Expand the ZBOT-2 two-phase CFD model to incorporate the active cooling components
- Validation: Validate the active cooling tank models with microgravity data
- Scale-up: Use the validated CFD models and empirical microgravity correlations to scale-up the design of the future tanks and their active cooling ZBO pressure control system

<table>
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<tbody>
<tr>
<td><strong>Accommodation (carrier)</strong></td>
</tr>
<tr>
<td><strong>Upmass (kg)</strong></td>
</tr>
<tr>
<td>(w/o packing factor)</td>
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<tr>
<td><strong>Volume (m³)</strong></td>
</tr>
<tr>
<td>(w/o packing factor)</td>
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<tr>
<td><strong>Power (kw)</strong></td>
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<tr>
<td>(peak)</td>
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<tr>
<td><strong>Crew Time (hrs)</strong></td>
</tr>
<tr>
<td>(installation/operations)</td>
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<tr>
<td><strong>Launch/Increment</strong></td>
</tr>
</tbody>
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ZBOT STATUS

- **ZBOT CDR** under way, Formal Review Scheduled for December 10, 2012
- **ZBOT Hardware** complete planned for December 2013
- **ZBOT flight hardware availability** planned for August 2014
- **ZBOT 2,3** still pre-phase A
Summary

- **ZBOT** ready to go soon!
- **ZBOT** provides valuable data for understanding Cryogenic Propellant Storage and Transfer:
  - Observation of tank fluid mixing in low gravity with condensing fluid
  - Accurate control of thermal environment with precise temperature measurement and control
  - Accurate measurement of fluid motion with laser Particle Imaging Velocimetry
- **ZBOT flight experiment** data will significantly improve the modeling of Cryogenic Propellant Storage and Transfer
- **ZBOT test hardware** extensible to several additional Cryogenic Propellant Storage and Transfer research efforts