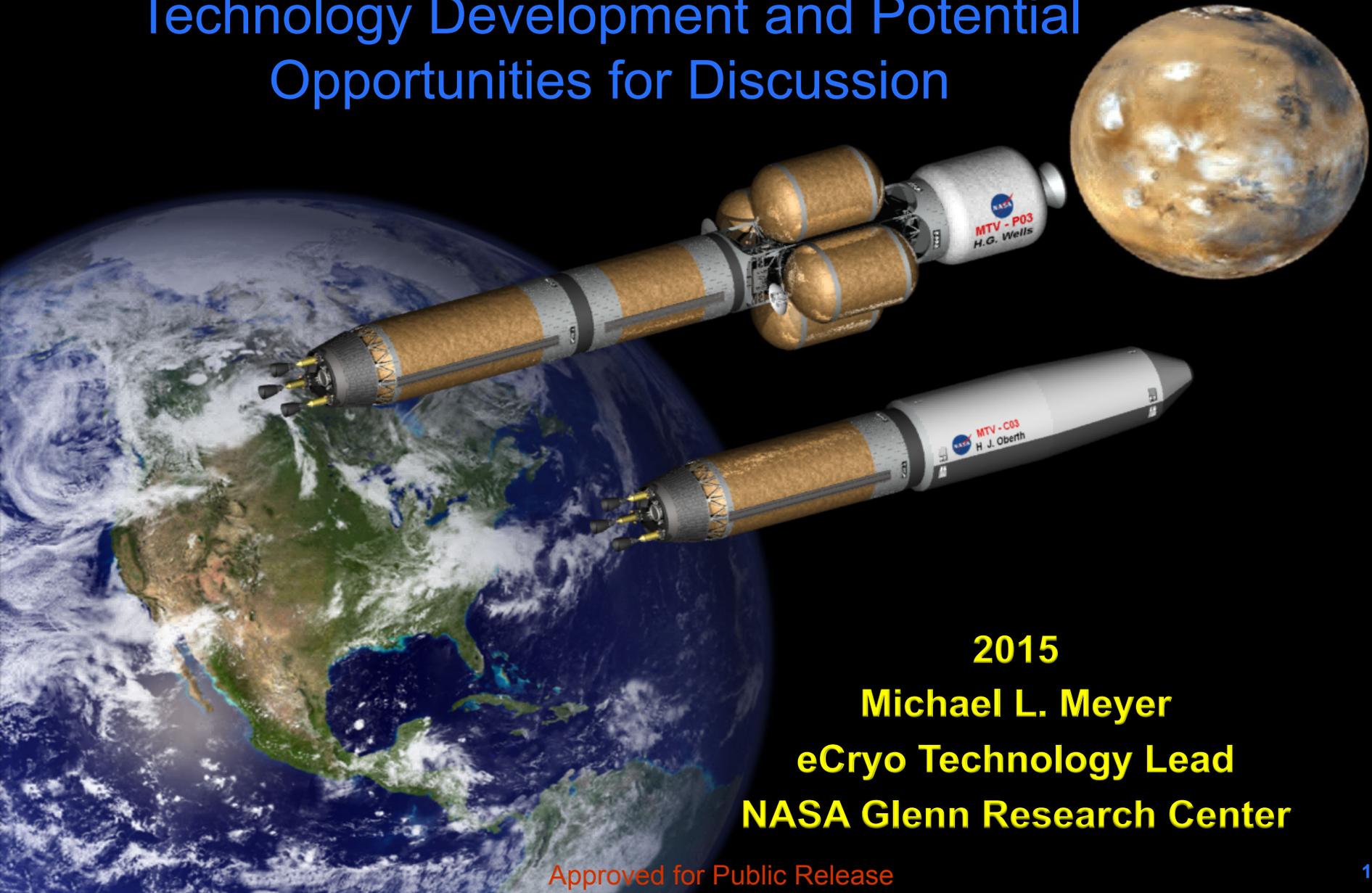


NASA Cryogenic Propellant Systems Technology Development and Potential Opportunities for Discussion



2015

Michael L. Meyer

eCryo Technology Lead

NASA Glenn Research Center



Outline

- Summary of CPST
- Summary of the technology work accomplished under CPST
- Opportunities for Future Cooperation
 - Discussion of eCryo content (including CFD)
 - Discussion of some existing/funded microgravity experiments (not cryogenic)
 - Discussion of as yet unfunded opportunities to obtain cryogenic microgravity performance data through collaboration



The Cryogenic Propellant Storage and Transfer (CPST) Mission Was on a Path to Obtain High Quality Microgravity Data on a Hydrogen System

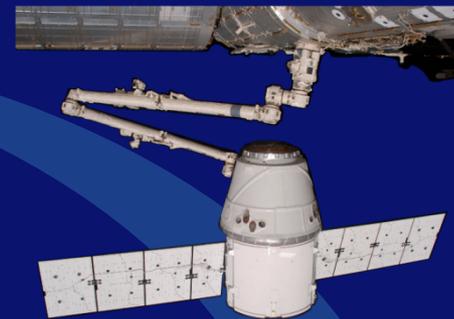
Extending human reach into deep space by advancing cryogenic propellant storage and transfer technologies to meet the needs of both NASA exploration systems and commercial launch providers

Passive Storage, Transfer, and Gauging Demo

Check-out



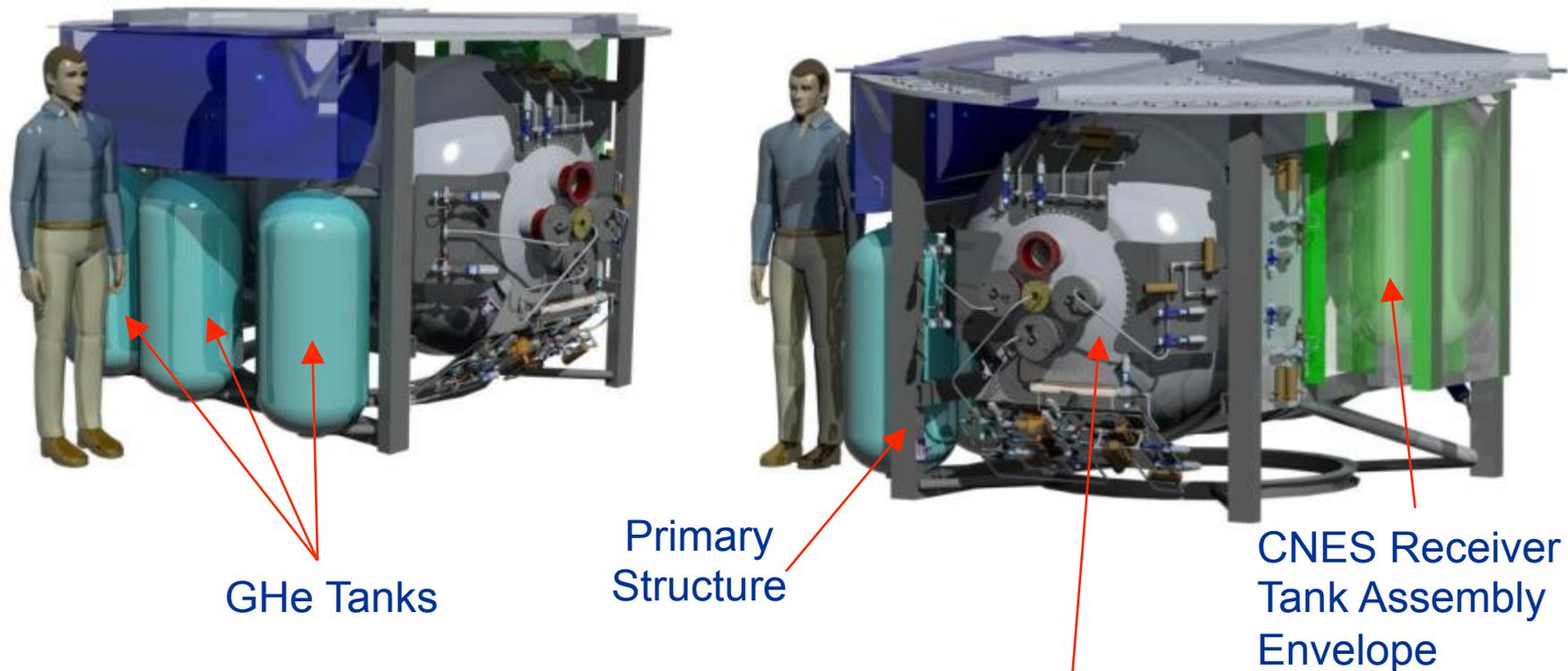
Dock to ISS



*Launch
2018*

- *Demonstrate long-duration storage*
- *Demonstrate in-space transfer*
- *Demonstrate in-space, accurate gauging*

CPST Payload



Driving Requirements

- Mission duration with technology demonstration content
- Safety requirements (SpaceX, Range, ISS) and associated design impacts for large hazardous LH2 payload (little precedence)
- SpaceX trunk allowable volume, and to lesser extent allowable mass



CPST Technology Maturation Phase Overview

Purpose of the Technology Maturation Phase of CPST:

Conduct tests, analytical modeling, and studies to mature technologies which were planned for the CPST demonstration flight in order to reduce the risk to cost and schedule for system development.

CPST Thermal Control: Penetration Heat Leak Study

Objective:

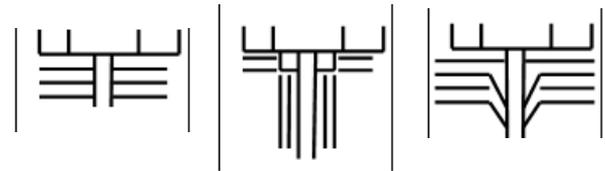
- Quantify thermal losses involving integrating MLI into real situations.

Approach:

- Test different integration methods & develop models specifically focused on the effects of penetrations (including structural attachments, electrical conduit/feedthroughs, and fluid lines) through MLI.

Results:

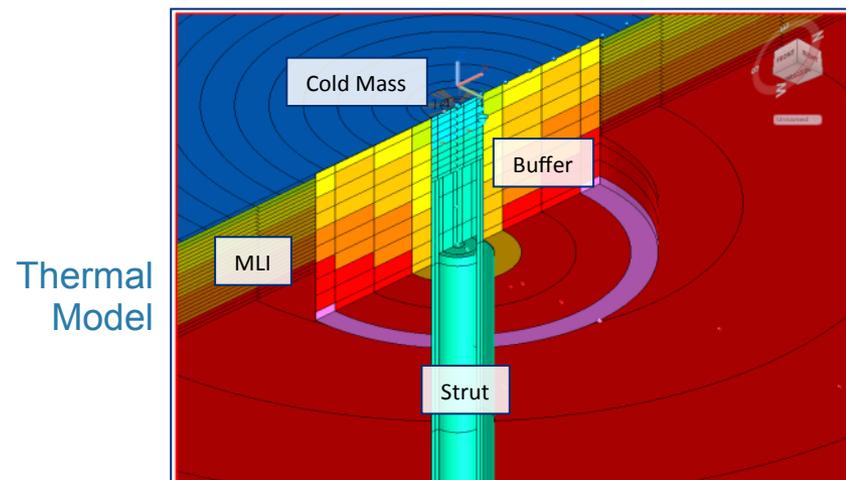
- Developed test method for measuring degradation of MLI around a penetration
- Measure heat load degradation and radius of thermally effected zone
- Determined the integration is best done with microfiberglass blankets
- Built & validated detailed thermal model of penetrations



Comparison of Different Integration Approaches



Calorimeter Test
Setup at KSC



CPST Thermal Control: Hydrogen Reduced Boil-off

Objective:

Validate concept to reduce boil-off of LH2 by integrating a ~90K cryocooler to intercept heat in the MLI and conductive loads.

- Address both thermal and structural concerns

Approach:

Constructed identical subscale tank test articles with broad area cooling (BAC) shields inside a thick MLI blanket.

- Thermal test article integrated with a reverse turbo Brayton cryocooler.
- Structural test article exposed to launch representative acoustic environment
- Self supporting MLI evaluated in Phase II of testing

Results:

- Acoustic tests resulted in no damage to MLI/BAC system
- Thermal testing demonstrated ~60% reduction in boil-off



Thermal test article
being lowered into
thermal vacuum
chamber



Structural test article
in acoustic chamber



CPST Thermal Control: Oxygen Zero Boil-off

Objectives

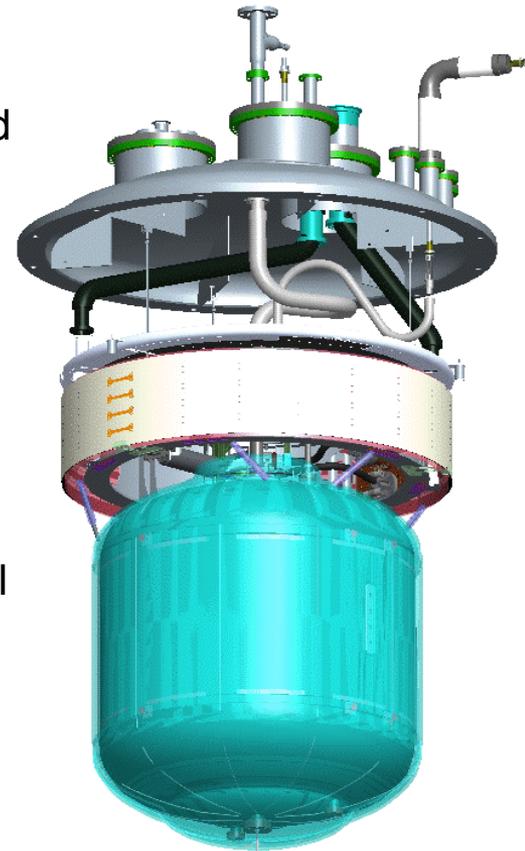
Quantify the system performance integrating a flight representative reverse turbo-Brayton cycle cryocooler for Zero Boil-Off (ZBO) storage of **Liquid Oxygen (LO2)** for extended duration in a simulated space environment

Approach

- Liquid Nitrogen was used as a surrogate fluid for LO2 to eliminate risks/costs associated with testing with LO2; testing conducted at elevated pressure to simulate LO2 storage temperature
- Test article included the following:
 - Flight representative test tank with circulator tubing stitch welded and epoxied to test tank; thick (74 layer) traditional MLI
 - Simulated space vacuum and thermal environment

Results

- Success in ground demonstration of active thermal control technologies that achieve ZBO of LO2
 - ZBO achieved at two storage tank fill levels: ~ 90% and ~25% full



3-D image of test article for LO2 ZBO validation

CPST Cryogenic Propellant Transfer: Transfer Line Chill-down

Objectives

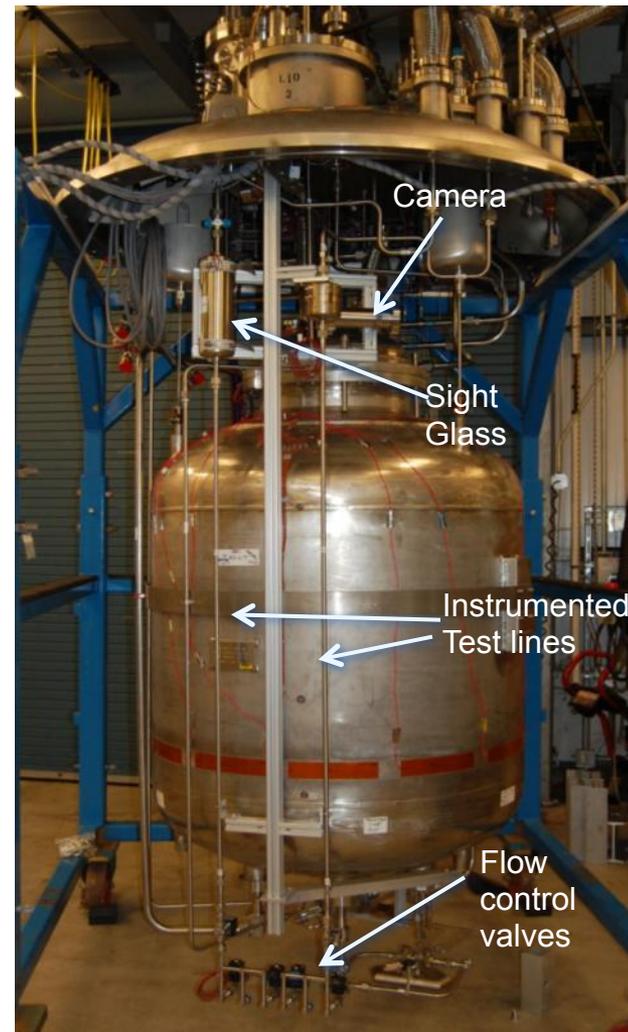
Evaluate efficient methods of pre-chilling a (tank-to-tank) transfer line of size representative of the CPST mission hardware.

Approach

- Construct a LH2 supply test tank with a transfer line of suitable diameter and length to roughly simulate the CPST system
- Test article included the following:
 - Vertical flow
 - Variable flow rates
 - Downstream flow visualization
 - Simulated space vacuum and thermal environment

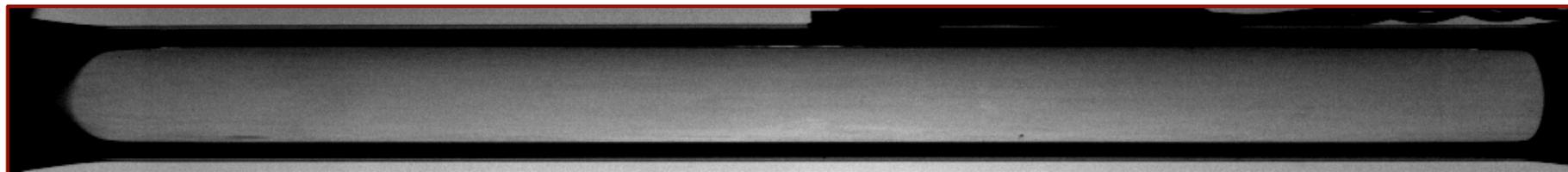
Results

- Successfully collected data on chill-down of the line varying several parameters.
- Compared temperature and pressure data to visual flow quality.
- Used data to develop simplified chill-down models.

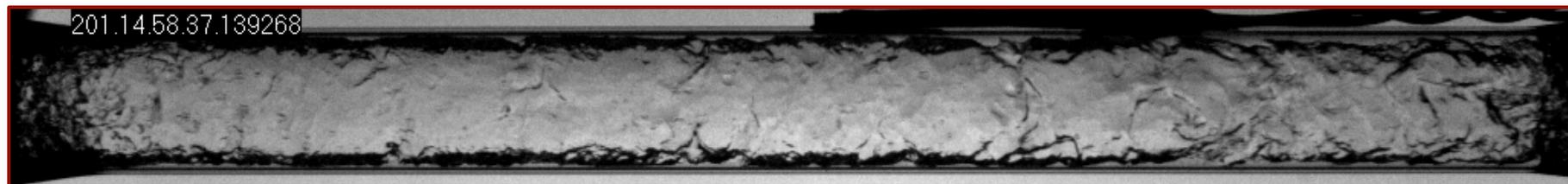


Line-Chill test article
prior to insulation

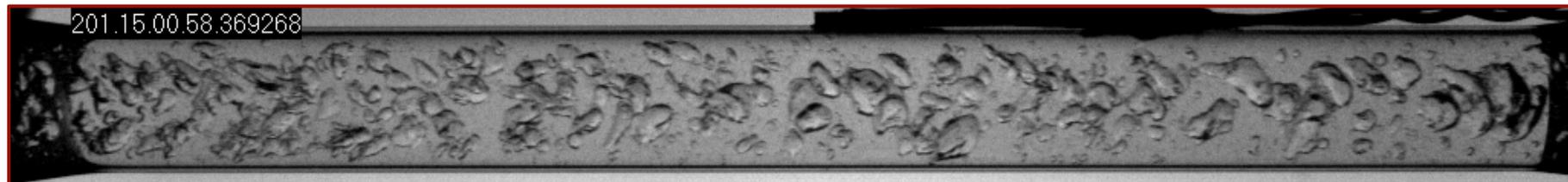
CPST Propellant Transfer: Transfer line Chill-down Visualization



LH₂ Gas to Droplet



LH₂ Wavy Annular Flow



LH₂ Bubbly Flow

CPST Propellant Gauging: Radio Frequency Mass Gauge (RFMG)

Objective:

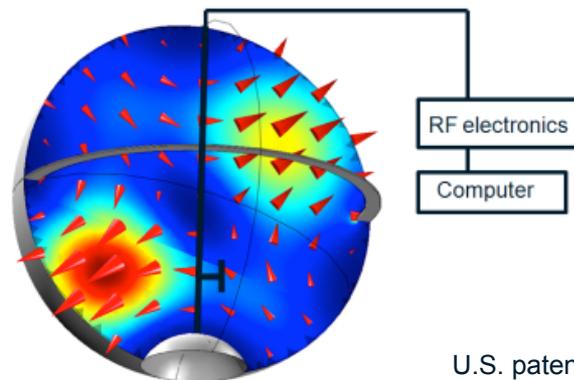
Continued maturation of a gauge technology capable of measuring the amount of liquid cryogenic propellant in the tanks of a vehicle in space without accelerating to settle the propellant

Approach:

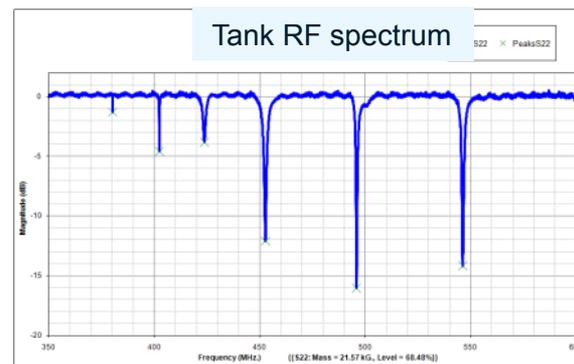
- Apply system developed in ground-based testing to a tank with a simulant fluid on a aircraft flying parabolic arcs for “zero-g”
- Mature electronics used for excitation and analysis of RF signal to enable a flight system.

Results:

- Successfully obtained microgravity data through multiple parabolic arcs and multiple configurations



U.S. patent # 8,353,209





SOME THOUGHTS FOR DISCUSSION OF POTENTIAL FUTURE COLLABORATION



The CPST Partnership Was Proving to be Very Fruitful



CNES Representatives with CPST Team at Face to Face Meeting in Cleveland



CPST has Transitioned to a (mostly) Ground-Based Project Called eCryo (evolvabe Cryogenics)

eCryo Task	Objective
Development & Validation of Analysis Tools (DVAT)	Advance the development and validation of analysis tools for settled and unsettled cryogenic fluid management in-space operations for long durations and large scales.
Improved Fundamental Understanding of Super Insulation (IFUSI)	Obtain thermal and structural performance data for various super insulation configurations and characteristics to enable the design of an insulation system for a large scale application.
Structural Heat Intercept-Insulation-Vibration Evaluation Rig (SHI-I-VER)	Learn at least one way to design, fabricate, and install stage-sized multi-layer insulation blankets Quantify the effectiveness of at least one structure-born heat intercept approach using cryogenic propellant vapor
Radio Frequency Mass Gauge (RFMG) Demonstration on ISS	Quantify the accuracy of an RFMG inside an unsettled fuel tank in a microgravity environment utilizing COTs components.
Vehicle Integrated Pressurization and Power System (VIPPS)	Develop an approach for applying the most promising integrated cryogen pressurization and electrical power generation system for EUS missions.



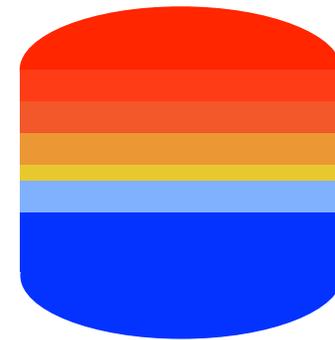
Development & Validation of Analysis Tools (DVAT)

Goal:

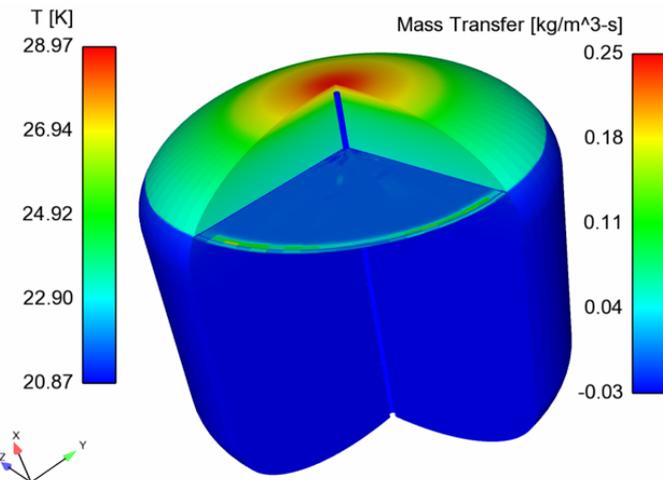
Advance the development and validation of analysis tools for settled and unsettled cryogenic fluid management in-space operations for long durations and large scales.

Objectives:

- Conduct CNES CFD benchmark collaboration.
- Extend multinode analysis tools to unsettled conditions.
- Validate multinode and CFD tools against 1-g experimental data for line chilldown, tank chilldown, tank filling, tank pressurization, self-pressurization, axial jet and spray bar thermodynamics vent systems and quasi-steady boil-off.
- Validate multinode and CFD tools against micro-g experimental data for self-pressurization, axial jet mixing and transfer operations.



Multinode with multiple ullage & liquid nodes



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



Improved Fundamental Understanding of Super Insulation (IFUSI)



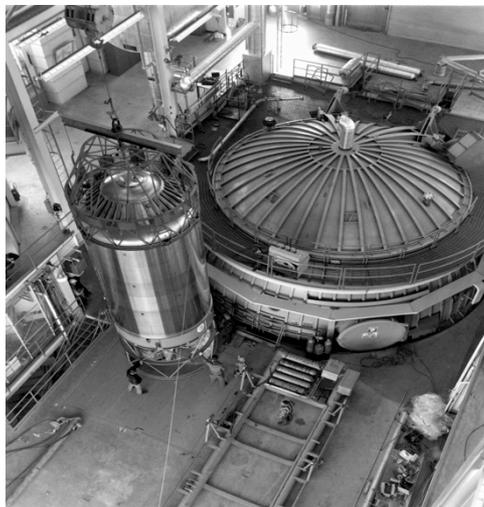
Approach uses a new cylindrical calorimeter

- ~0.5 m diameter , 1.2 m high
- Wide temperature range options for inner (down to LH2 temperatures) and outer boundaries (90K to ambient)
- Perform thermal testing on hybrid MLI and seam configurations.
- Perform thermal testing to determine low temperature transmissivity of typical MLI components.
- Perform thermal repeatability testing on representative insulation systems.
- Perform structural testing on attachment mechanisms.

Structural Heat Intercept-Insulation-Vibration Evaluation Rig (SHI-I-VER)

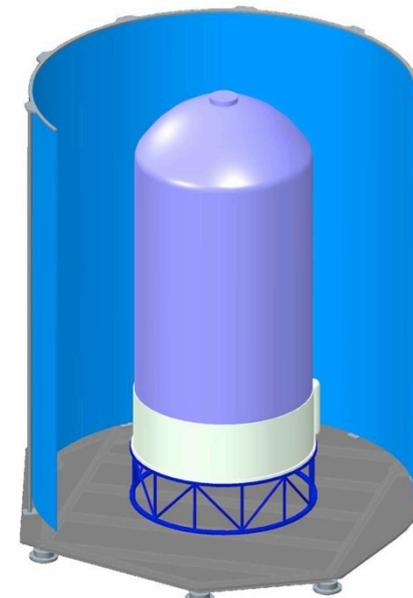
Objectives:

- Very large scale tank insulation investigation (Tank 4+ m diameter)
 - Structural Performance
 - Thermal Performance
- Vapor Based Heat Intercept
- Designed to enable future active cooling demonstration
- Intended to be able to accept technology from future partners
- First Test in 2017



Centaur Stage Above Plum Brook B-2 Vacuum Chamber

B-2 Vacuum Chamber



SHI-I-VER Test Article Concept

Radio Frequency Mass Gauge (RFMG) Demonstration on ISS

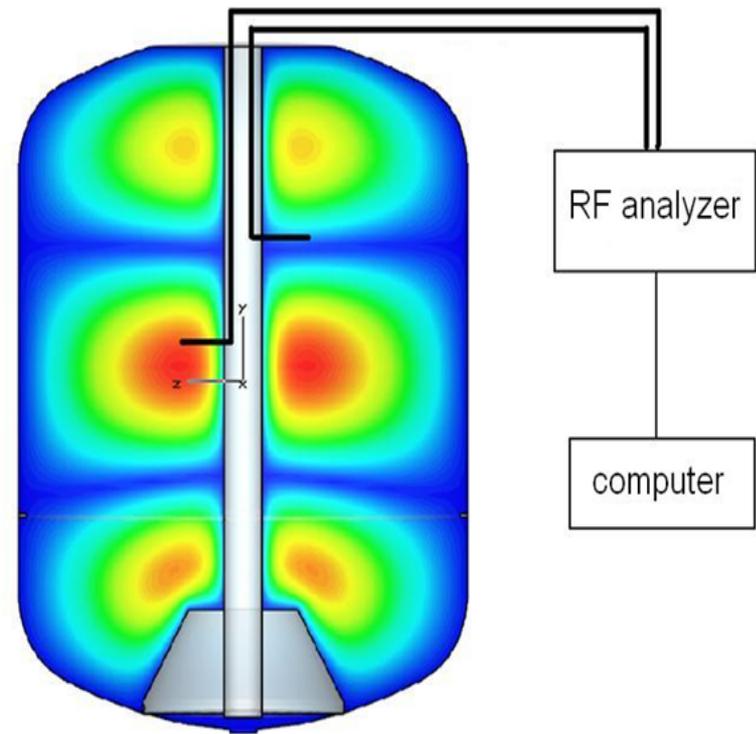
Approach:

Install a Radio Frequency Mass Gauge (RFMG) on the Robotic Refueling Mission 3 (RRM3)

- RRM3 is multi-phased International Space Station (ISS) technology demonstration that is testing tools, technologies and techniques to refuel and repair satellites in orbit
- An external payload

Objectives:

- Build a flight RFMG system capable of obtaining data in a microgravity environment.
- Perform gauging experiments inside an unsettled fuel tank in a microgravity environment.
- Quantify the accuracy of an RFMG inside an unsettled fuel tank in a microgravity environment utilizing COTs components.





20W 20K Cryocooler for Thermal Control of Space-Based Liquid Hydrogen

Under NASA STMD's Game Changing Development Program, NASA GRC is leading the development of a prototype 20W 20K Cryocooler

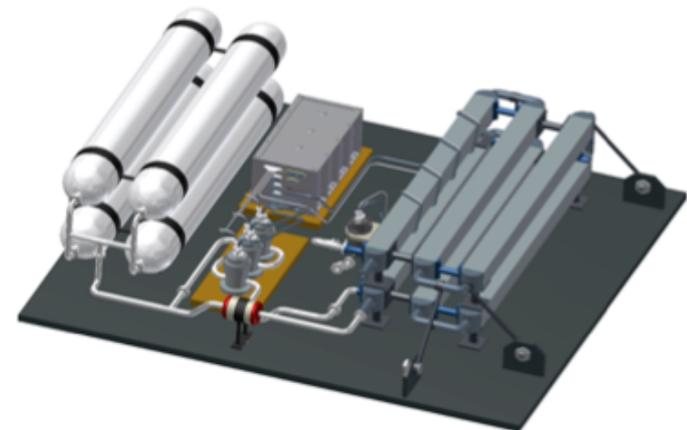
- This represents a major step forward in State of the Art for 20K cryocoolers, expected to provide 20W of thermal lift at a specific power of 70W/W and a specific mass of 5kg/W.
- This development is expected to serve as the technological foundation for the larger cryocoolers needed to maintain Zero Boil Off (ZBO) of a large Liquid Hydrogen (LH2) propellant tank at 20 K.

Objectives:

Advance the Technology Readiness Level of a 20W 20K Cryocooler for use within a NASA future-defined Liquid Hydrogen Zero Boil Off test

Approach:

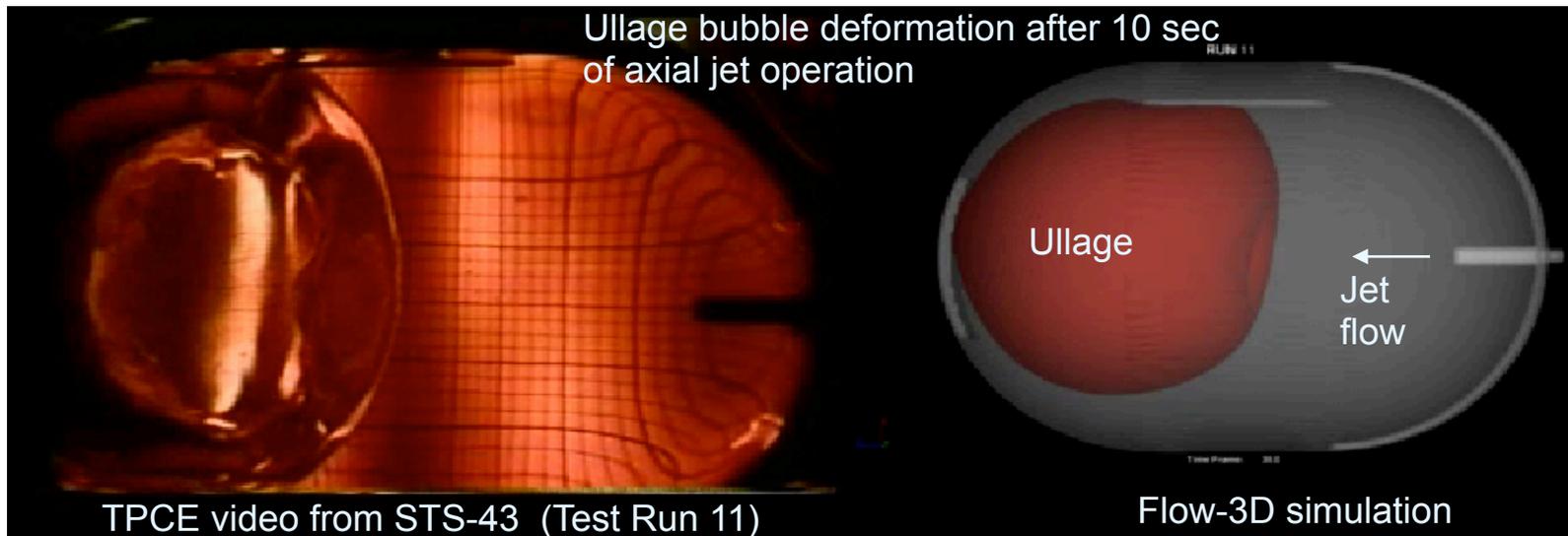
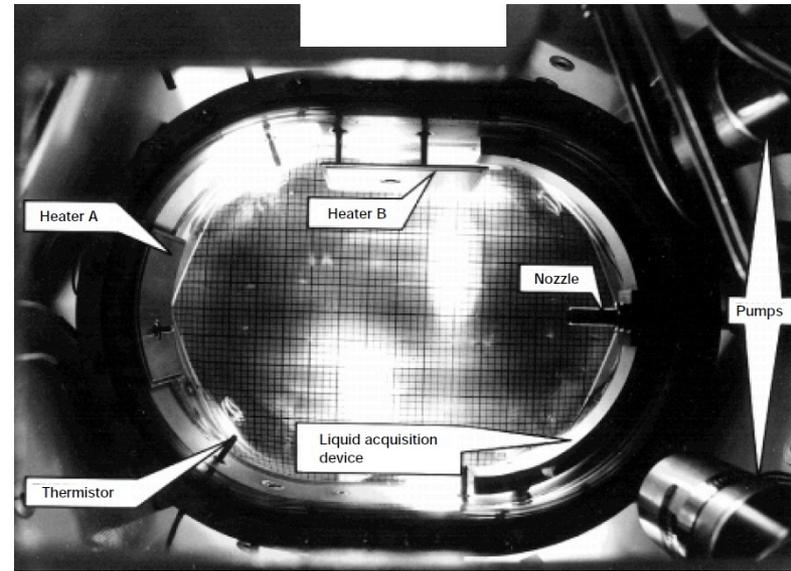
- Design and fabricate components (compressor, alternator and recuperative heat exchanger) for a 20W 20K cryocooler
- Integrate and acceptance test the Cryocooler under thermal vacuum conditions
- Deliver the cryocooler hardware and control rack to GRC.



20W 20K Cryocooler Concept

CFD Validation of micro-g axial jet mixing in Shuttle Tank Pressure Control Experiment (TPCE)

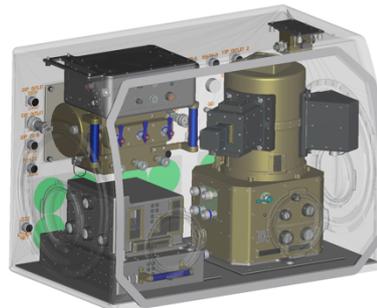
- 25.4 cm (10 in) diameter by 35.56 cm (14 in) long cylindrical tank with hemispherical domes was constructed of transparent acrylic plastic
- Filled with Freon-113: 83% liquid fill for Shuttle flight STS-43 (1st flight of this hardware in 1991)
- Validation below is considering only the fluid dynamics of an axial jet interacting with an ullage bubble in micro-g
- Future simulations will include heat and mass transfer between liquid and ullage, and will evaluate Fluent as well as Flow-3D



Zero Boil-Off Tank Experiment (ZBOT): Fluid Mixing



PI: Dr. Mohammad Kassemi, NCSSER/GR
Co-I: Dr. David Chato, NASA GRC
PS: John McQuillen, NASA GRC
PM: William Sheredy, NASA GRC
Engineering Team: ZIN Technologies, Inc



ZBOT in Microgravity Glovebox

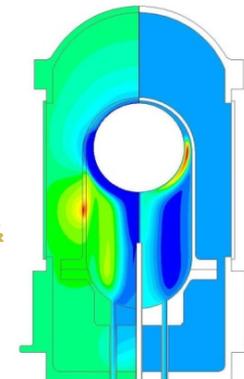


ZBOT EM Test Tank

Objective:

- ◆ Develop a small-scale transparent simulant-fluid ISS flight experiment to study storage tank thermal stratification, pressurization & pressure reduction through fluid mixing in microgravity.
- ◆ Gather high fidelity microgravity data under known/controlled conditions for verification & validation of storage tank CFD models.
- ◆ Formulate much-needed microgravity empirical correlations for thermal stratification, pressurization, liquid mixing, pressure reduction, and interfacial heat and mass transfer.

CFD Model: Temp & Flow Fields in Microgravity



Development Approach:

- ◆ **Ground Phase:** Develop ground-based experiment and obtain 1-g data for tank pressurization and pressure reduction.
- ◆ **Flight Phase:** Construct ISS experiment/hardware and obtain microgravity data for tank pressurization and pressure reduction.
- ◆ **Modeling:** Develop a state-of-the art two-phase CFD model for tank pressurization and pressure control.
- ◆ **Validation:** Validate and Verify the CFD model with microgravity and 1g data.
- ◆ **Scale-Up:** Use the validated CFD model and empirical correlations derived from the 1g and microgravity data for scale-up tank design.

Project Life Cycle Schedule

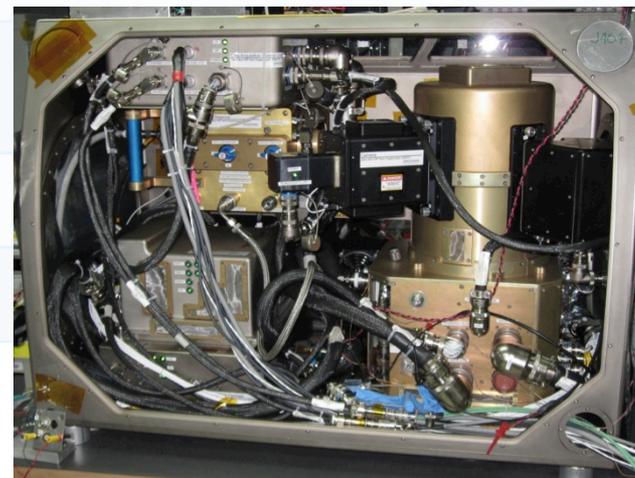
Milestones	SCR	RDR	PDR	CDR	VRR	Phase III Safety	FHA	Launch	Ops Complete	Final Report
Actual/ Baseline	7/2006	6/2008	2/2010	12/2012	3/2014	5/2015	7/2015	9/2015 –SPX-8	2/2016	2/2017



Zero Boil-Off Tank Experiment (ZBOT): Fluid Mixing

ISS REQUIREMENTS

Accommodation (carrier)	Microgravity Science Glovebox (MSG)
Upmass (kg) (w/o packing factor)	114 Kg
Volume (m ³) (w/o packing factor)	0.23 m ³
Power (kw) (peak)	0.445 kw (314 W max continuous)
Crew Time (hrs) (installation/operations)	13 hrs
Autonomous Operation	384 hrs
Launch Date – Vehicle	9/2015 – SpaceX-8



ZBOT Engineering Model in the Microgravity Science Glovebox (MSG) Work Volume Mockup

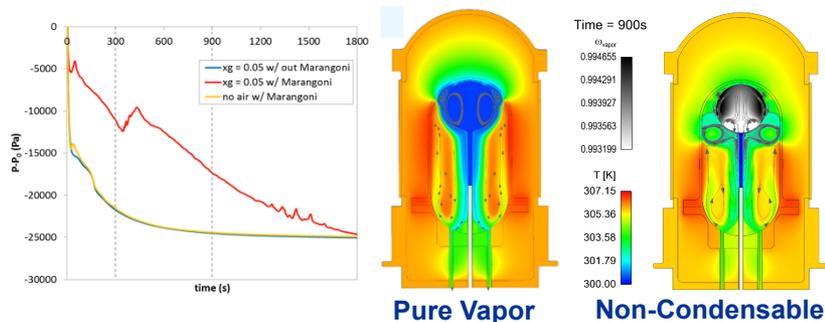


ZBOT-2-OS: Noncondensable Gas Effects

ZBOT-3-OS: Active Pressure Control

ZBOT-2 Objective:

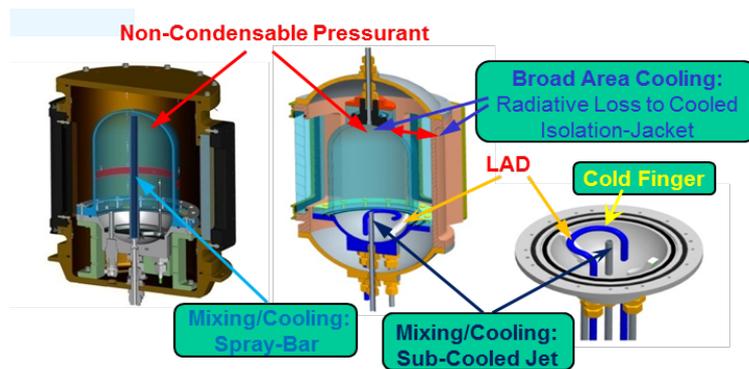
- ◆ Noncondensable gases can affect Zero-Boil-Off (ZBO) storage tank pressurization and pressure control, especially, in microgravity.
- ◆ Investigate the effects of noncondensables on the transport and phase change phenomena that control tank pressure. These effects can be best studied when they are readily unmasked in microgravity:
 - The impact of noncondensable on microgravity vapor transport in the ullage during pressurization.
 - The creation of thermocapillary convection induced by noncondensable and its effect on mixing, stratification and destratification in the liquid.
 - Formation of transport barrier and/or penetration of noncondensables into the Knudsen layer and their impact on condensation rates.



Hand-in-Hand Microgravity & 1G Experimentation & Computational Modeling

ZBOT-3 Objective:

- ◆ Examine different modes of active pressure control such as axial jet, spray-droplet, and broad area cooling.
- ◆ Obtain microgravity data on spray breakout, and droplet transport and phase change in microgravity
- ◆ Investigate effect of noncondensable on droplet phase change
- ◆ Establish a microgravity foundation for comparison and optimization of the different active cooling strategies for future storage pressure control design.



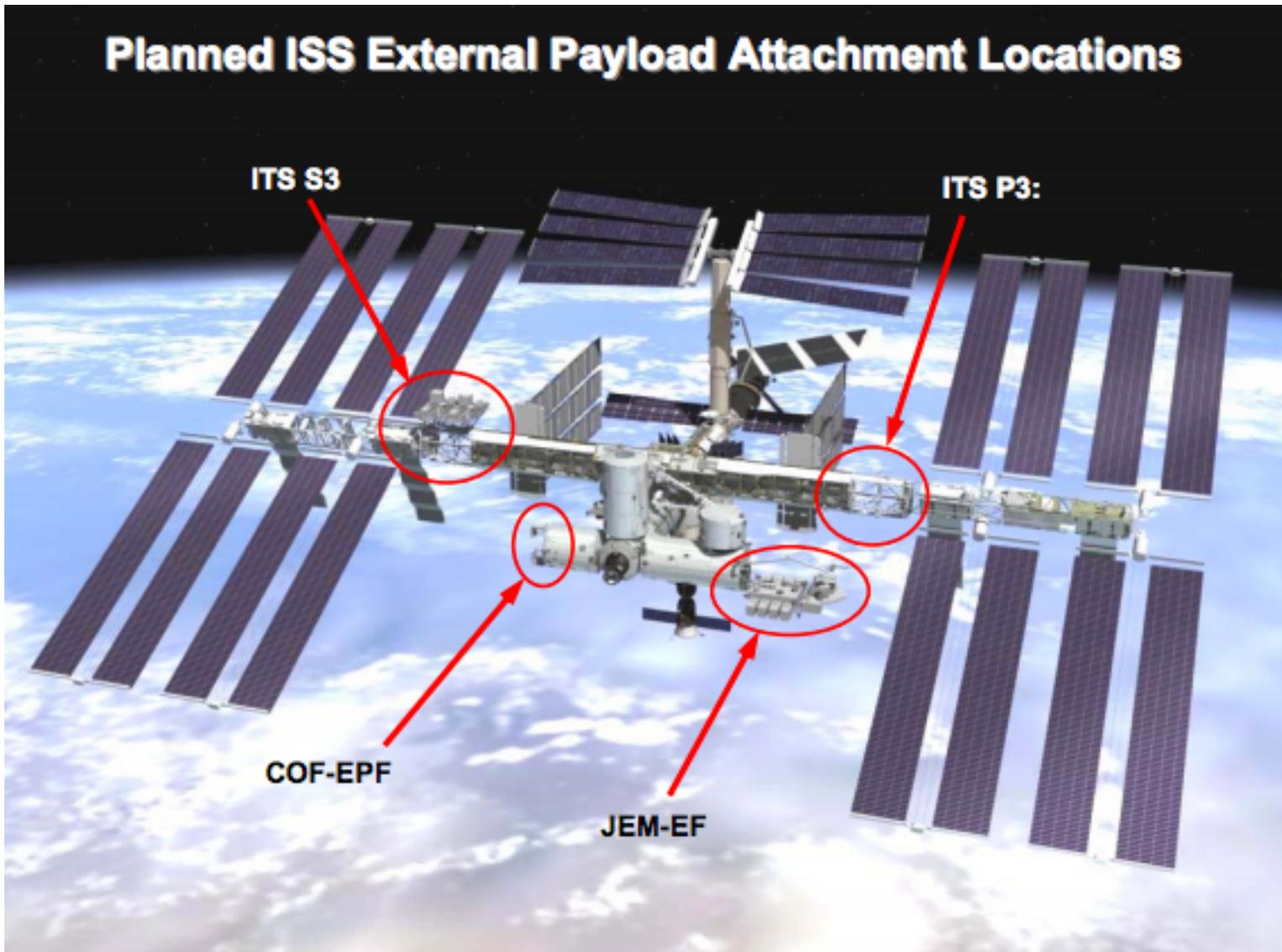
Project Life Cycle Schedule

Milestones ZBOT-2	Kickoff	SCR/RDR	PDR	CDR/VRR	Phase III Safety	FHA	Launch	Ops Complete	Final Report
Actual/ Baseline	10/2015	9/2016	9/2017	9/2018	7/2019	9/2019	1/2020	3/2020	3/2021
Milestones ZBOT-3	Kickoff	SCR/RDR	PDR	CDR/VRR	Phase III Safety	FHA	Launch	Ops Complete	Final Report
Actual/ Baseline	10/2018	9/2019	9/2020	9/2021	7/2022	9/2022	1/2023	3/3023	3/2024



Potential Future Microgravity Opportunities

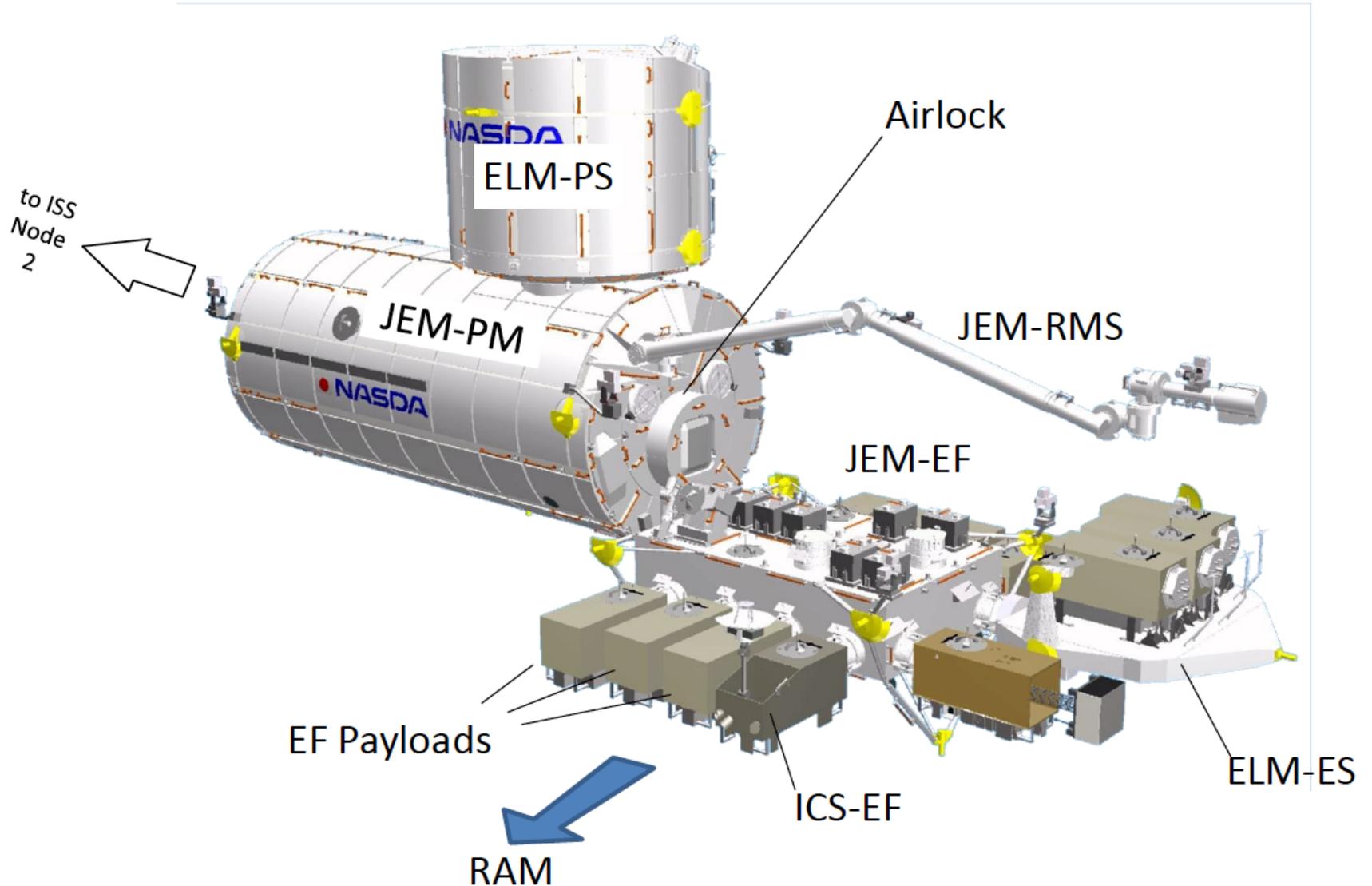
- To obtain microgravity fluid/thermal behavior data for anchoring CFD and other analytical techniques, we are interested in exploring the concept of a multi-Agency microgravity experiment
 - Sounding Rocket (suggested by CNES as possible opportunity to collaborate)
 - We have also taken a cursory look at an ISS external pallet type experiment
 - The next few slides provide a little information to start discussion on this concept



International Space Station External Payload Accommodations, ISS Technology Demonstration Office Research Integration Office, ISS Accom-110612

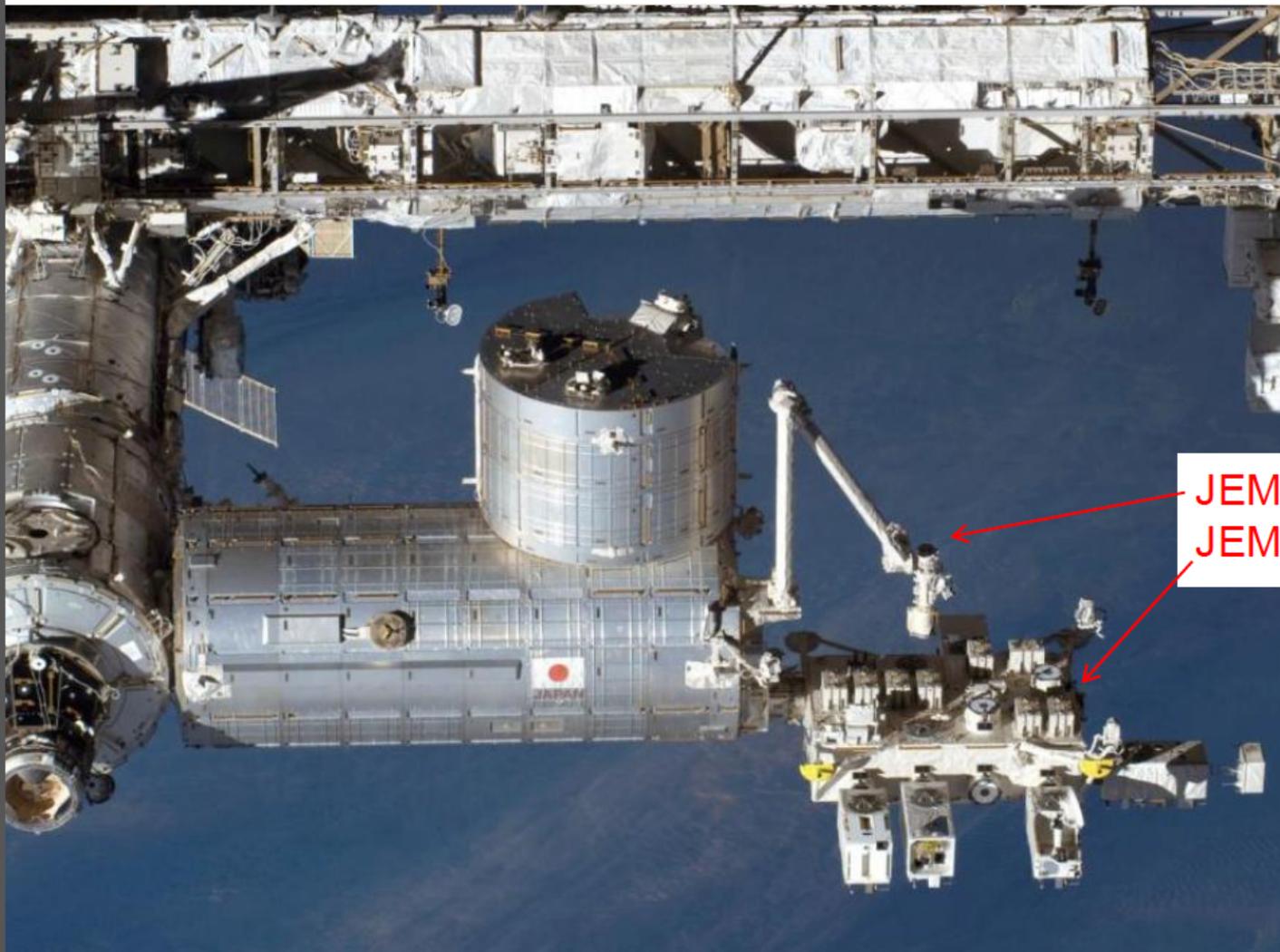


Japanese Experiment Module Exposed Facility (JEM EF) Overview





Japanese Experiment Module - *Kibo*



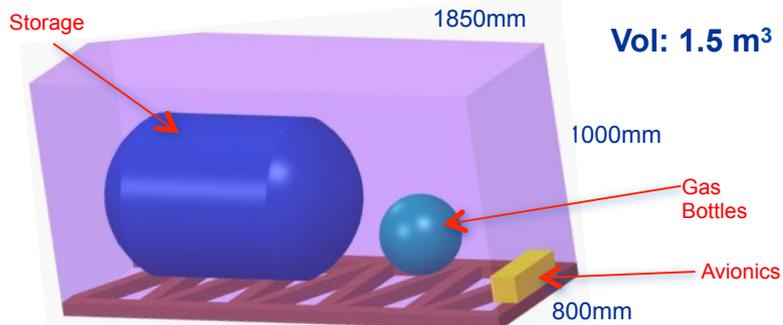
JEM RMS
JEM External Facility

International Space Station External Payload Accommodations, ISS Technology Demonstration Office Research Integration Office, ISS_Accom-110612

Approved for Public Release

eCryo ISS External Experiment Concepts

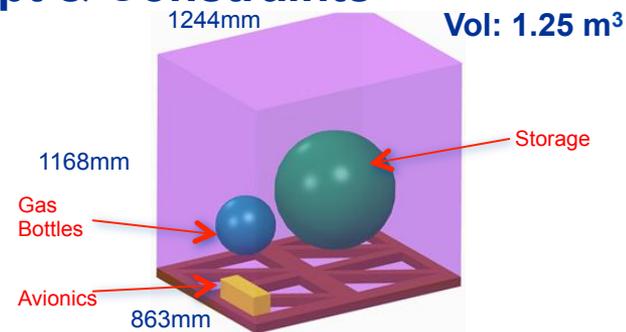
JEM EF Concept & Constraints



Vol: 1.5 m³

Mass: 550 Kg (standard site)/ 2,250 Kg (heavy site)
Power: 3-6 kW, 113 – 126 VDC
Data: 1 Mbps (MIL-STD-1553, 2-way), 1EEE-802.3(10BASE-T, 2-way), 43 Mbps (shared, 1-way downlink)
Thermal: 3-6 kW cooling

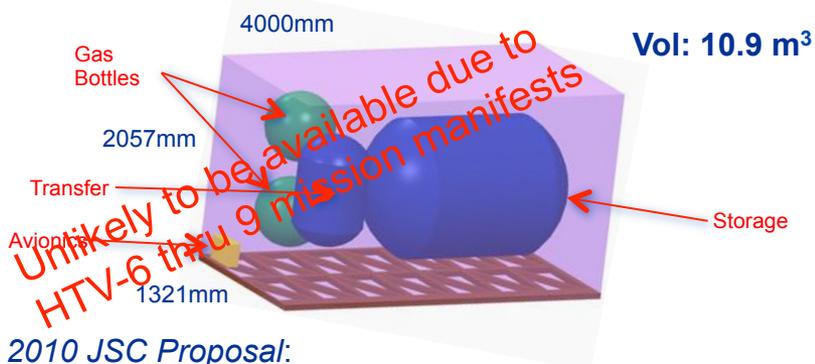
ELC Concept & Constraints



Vol: 1.25 m³

Mass: 227 Kg
Power: 750 W, 113 – 126 VDC; 500 W at 28 VDC/adapter
Data: 1 Mbps (MIL-STD-1553) , 6 Mbps (shared) - Return link (payload to ISS) only
Thermal: Active heating, passive cooling

HTV EP Concept & Constraints



From 2010 JSC Proposal:
Mass: 1,500 Kg
Power: 1 kW average, 100 W keep-alive, 3 kW max
Data: 1553, Ethernet, HRDL
Thermal: ???

CAPABILITIES PER SITE	JEM	ELC	HTV EP
Heat Intercept (Insulation System)	✓	✓	✓
Heat Intercept (Vapor-based)	✓	✓	✓
Heat Intercept (Cryocooler based)	✓		
Heat Removal (TVS)	✓	✓	✓
Pressurization		✓	✓
Transfer			✓

NOTIONAL SCHEDULE

Oct 2015 Funding	Oct 2017 Fab	Oct 2018 Test	Jun 2019 Deliver	Dec 2019 Launch
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