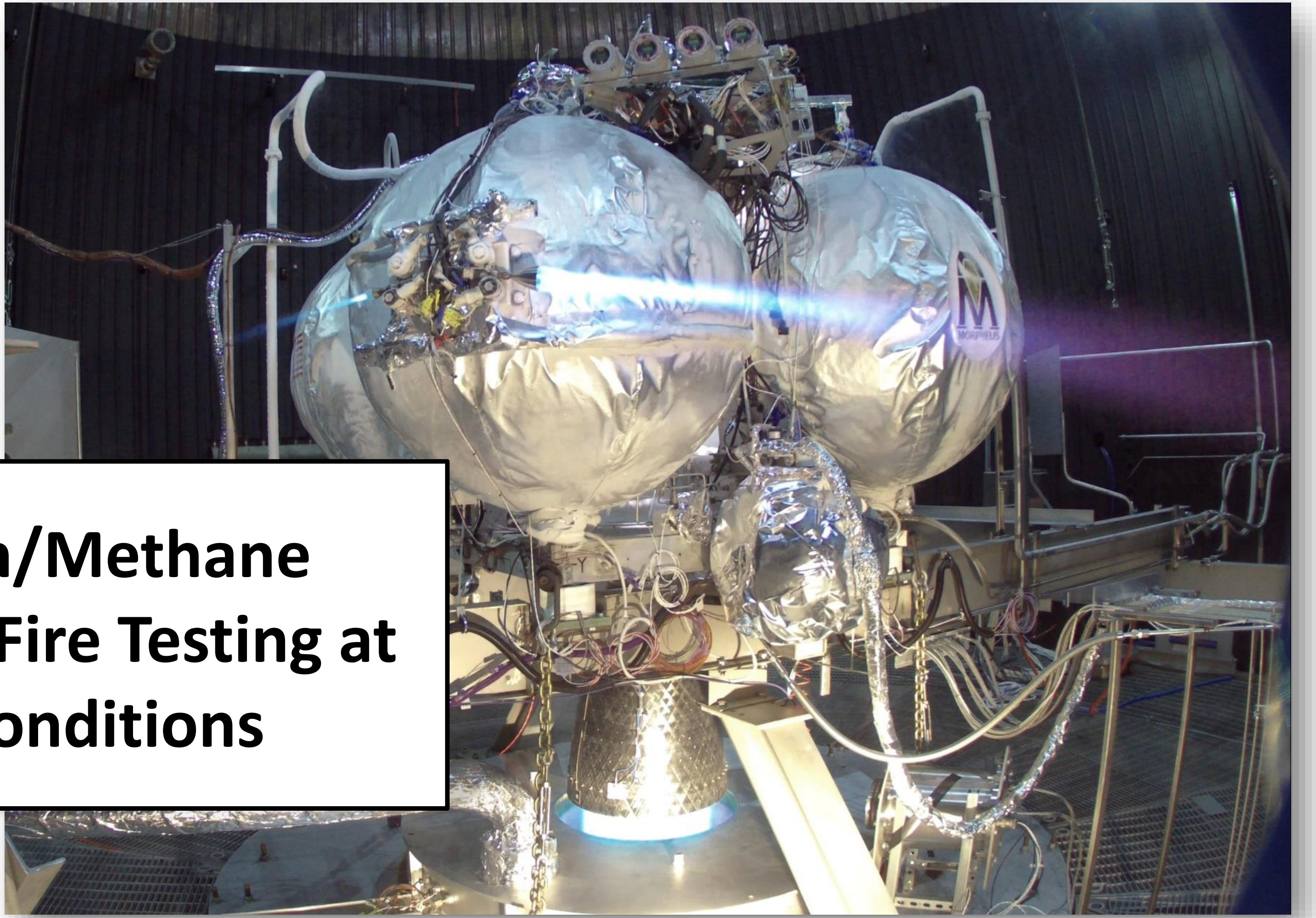
Thermal and Fluids Analysis Workshop
Galveston, TX, 2018

Vehicle-Level Oxygen/Methane Propulsion System Hot-Fire Testing at Thermal Vacuum Conditions

Material from AIAA-2017-4748



ICPTA Combo hotfire test, 2/28/17

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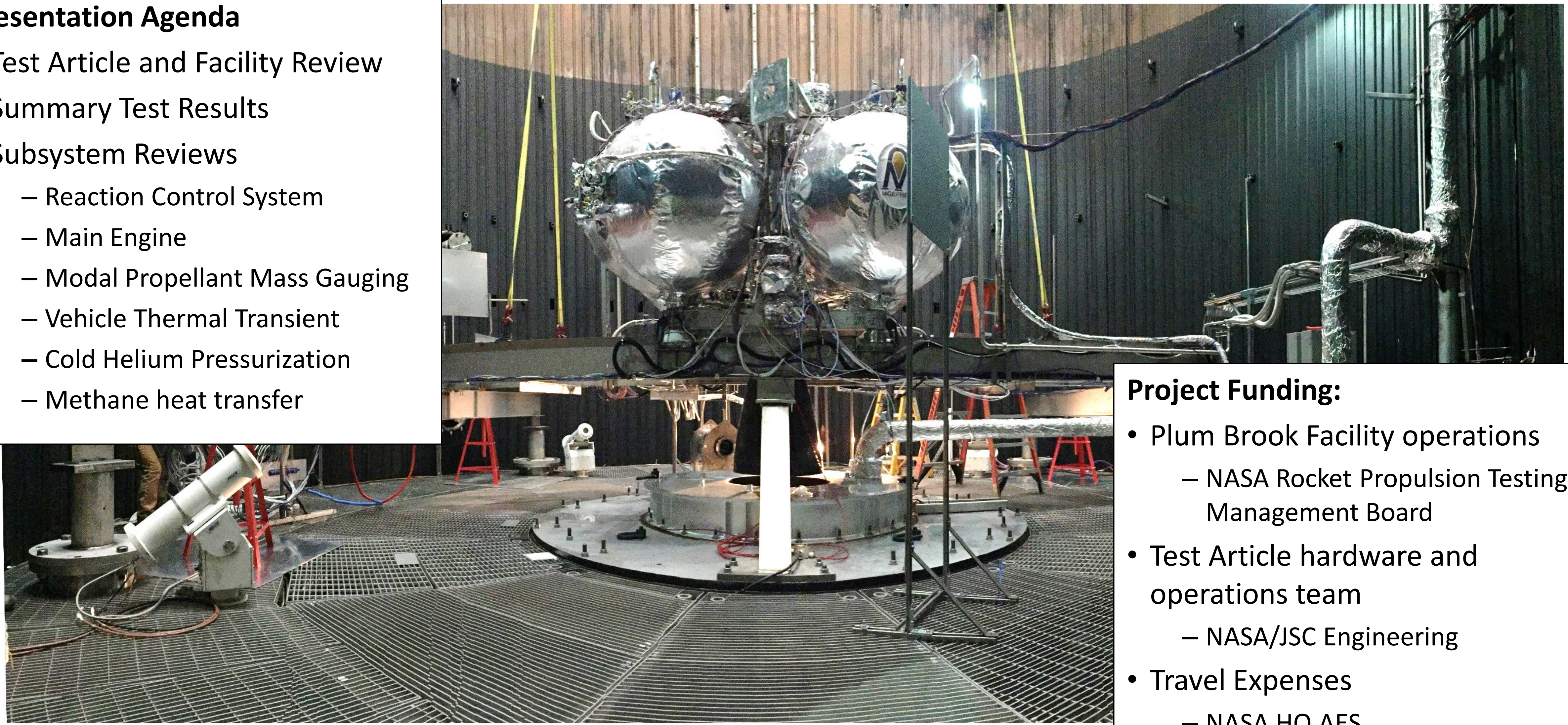
August 22, 2018

Integrated Cryogenic Propulsion Test Article (ICPTA) in Plum Brook ISPF (B2) Test Cell



Presentation Agenda

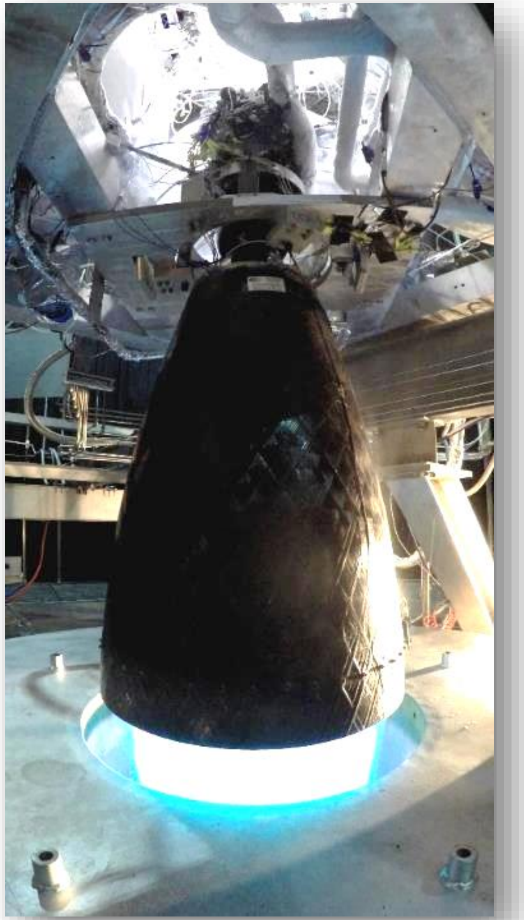
- Test Article and Facility Review
- Summary Test Results
- Subsystem Reviews
  - Reaction Control System
  - Main Engine
  - Modal Propellant Mass Gauging
  - Vehicle Thermal Transient
  - Cold Helium Pressurization
  - Methane heat transfer

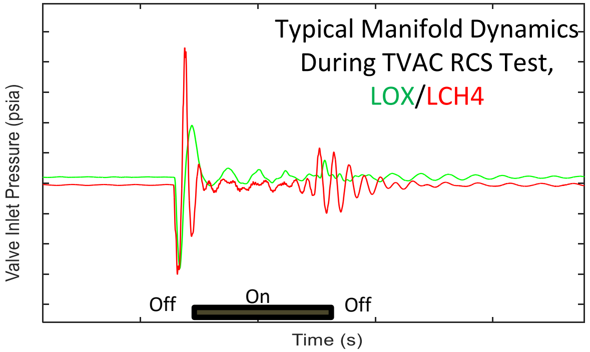
Project Funding:

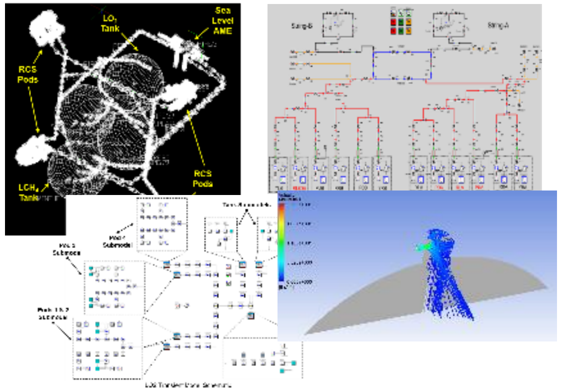
- Plum Brook Facility operations
  - NASA Rocket Propulsion Testing Management Board
- Test Article hardware and operations team
  - NASA/JSC Engineering
- Travel Expenses
  - NASA HQ AES

Test Objectives Overview

- Provide ME and RCS thrust for Plum Brook facility characterization
- Collect LOX/Methane vehicle model validation data for a variety of experiments (320+ sensors on ICPTA)
  - System-level model verification: RCS manifold transient fluids, ME+RCS dynamics, vehicle thermal, cold helium pressurization / ullage collapse
  - Subsystem model verification: RCE/ME performance, Tank/Line insulation, Modal propellant mass gauging, Methane heat transfer, internal tank chill system
  - Subsystem demonstration: coil-on-plug ignition, facility nozzle diffuser (w/blowback), others
- Timeline: 6 Weeks of testing at Plum Brook ISPF (B2)
  - Dozens of RCS, ME, ME+RCS, loading, chill, thermal tests
  - Ambient temp / deep thermal, High altitude / soft vacuum
  - Joint operations: PB operated environment and prop loading, JSC operated vehicle
- JSC, KSC, GRC, SSC team focused on LOX/Methane research and other experiments





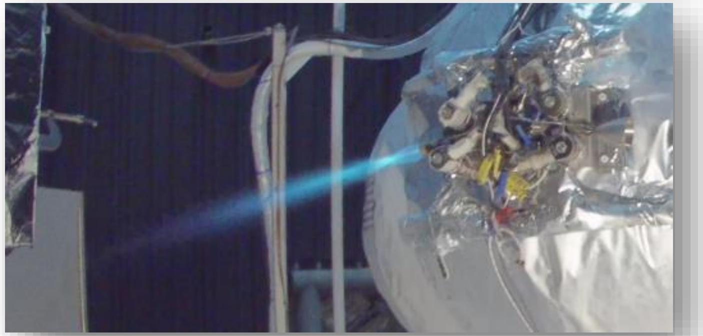


Numerous math models: fluids, thermal, SS/transient

Plum Brook Test Campaign Results

- **Accomplishments for test campaign, LOX/Methane research, and tech development:**
  - Multiple main engine tests up to 56 sec duration, sufficient to characterize the Plum Brook facility
  - 800+ Reaction Control Engine ignitions: numerous system operational modes including propellant self-priming
    - Vehicle RCS hotfires at deep cryo thermal vacuum conditions with thermal-related no-lights observed
  - Modal Propellant Mass Gauging performance data collected during hotfire and propellant loading/draining
  - Cryo Fluid Management: Line/Tank chill heat transfer data collected for liquid methane and liquid oxygen/nitrogen; demonstrated vehicle methane tank spray cooling system
  - Coil-on-Plug ignition system tested at vehicle level in high corona risk range
  - Cold Helium Pressurization of a cryo propellant at flight-like conditions
  - Numerous other minor experiments

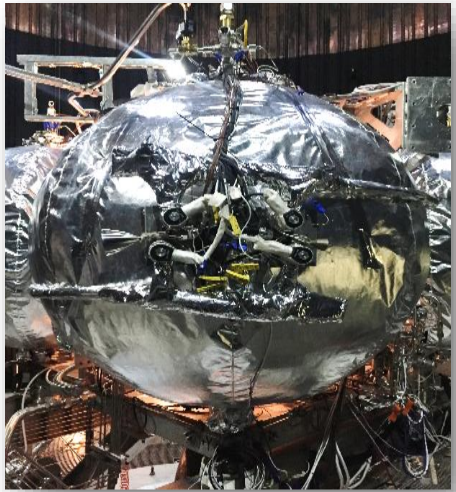
ICPTA RCS+ME hotfire test, 2/28/17



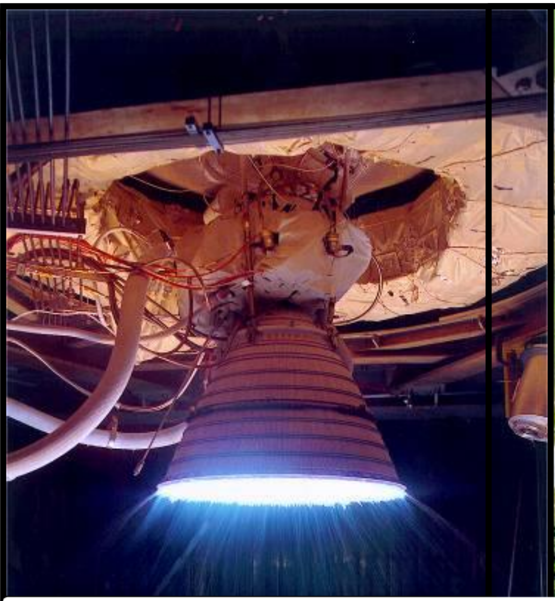
TVAC Hotfire of 7lbf Jet
3/9/17

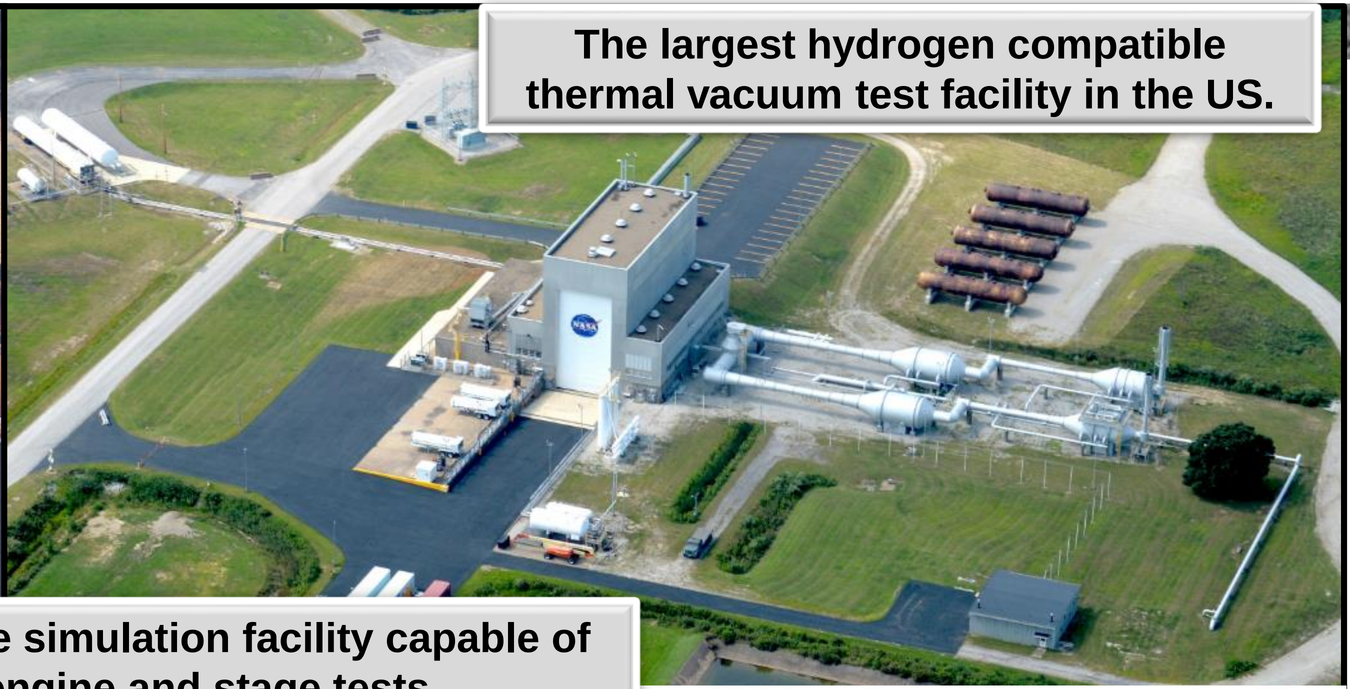
ICPTA Design Overview

- Lander configuration (tested w/o legs), central main engine, pod-mounted reaction control engines on vehicle perimeter
- 4x 48” spherical tanks (2ea. LOX / Methane) insulated with MLI + aerogel
- Common plumbing for main and RCS engines, insulated with MLI + aerogel
- RCS engines: Two pods (7lbf + 28lbf in each)
  - Coil-on-Plug ignition, 85:1 nozzles
  - Gas/Gas, Gas/Liquid, Liquid/Liquid operation; 100msec → SS ops
- Main Engine
  - 2,800 lbf Vac, 5:1 throttling, thrust measurement system
  - Coil-on-plug (COP) ignition, O2/CH4 igniter, 100:1 composite ablative nozzle
- Helium Pressurization
  - COPV with vac rated foam + MLI, LN2 cooling systems
  - High pressure HEX on ME Nozzle, warm gas reg panel, flowmeters, diffusers in prop tanks
- Flight computer external to test cell w/50-ft harness
- 320+ static/dynamic sensors on vehicle: temp, press, accel, load, strain, mics, etc
- Piezoelectric Mass Propellant Gauging (MPG) system
- CFM Experiments: Internal Tank Chill, facility/vehicle cryo loading heat transfer
- 4 load cell interface for vehicle to structure: real-time weight
- Multiple heaters on vehicle and around test cell
- Fluids: 4800 lbm LOX, 1800 lbm Methane, 7lb helium



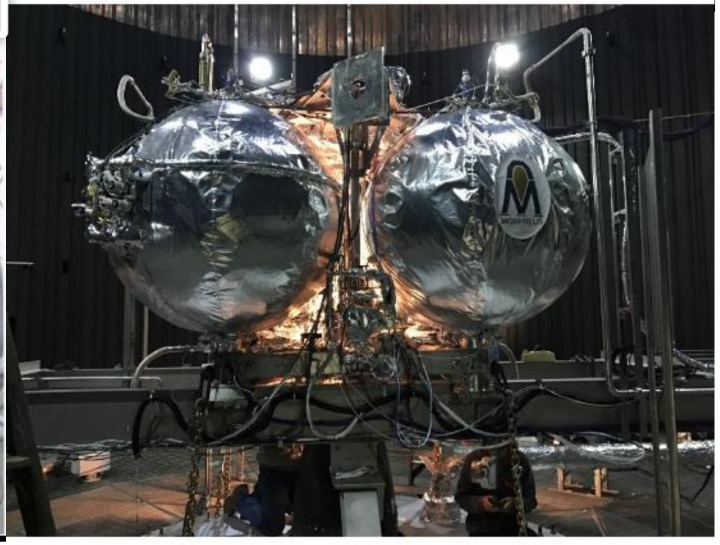
NASA Plum Brook Station In-Space Propulsion Facility (B-2)





The largest hydrogen compatible thermal vacuum test facility in the US.

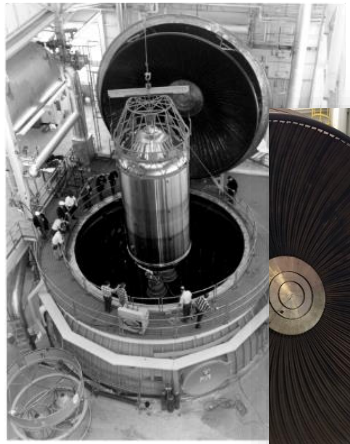
The world's largest space simulation facility capable of full-scale rocket engine and stage tests.

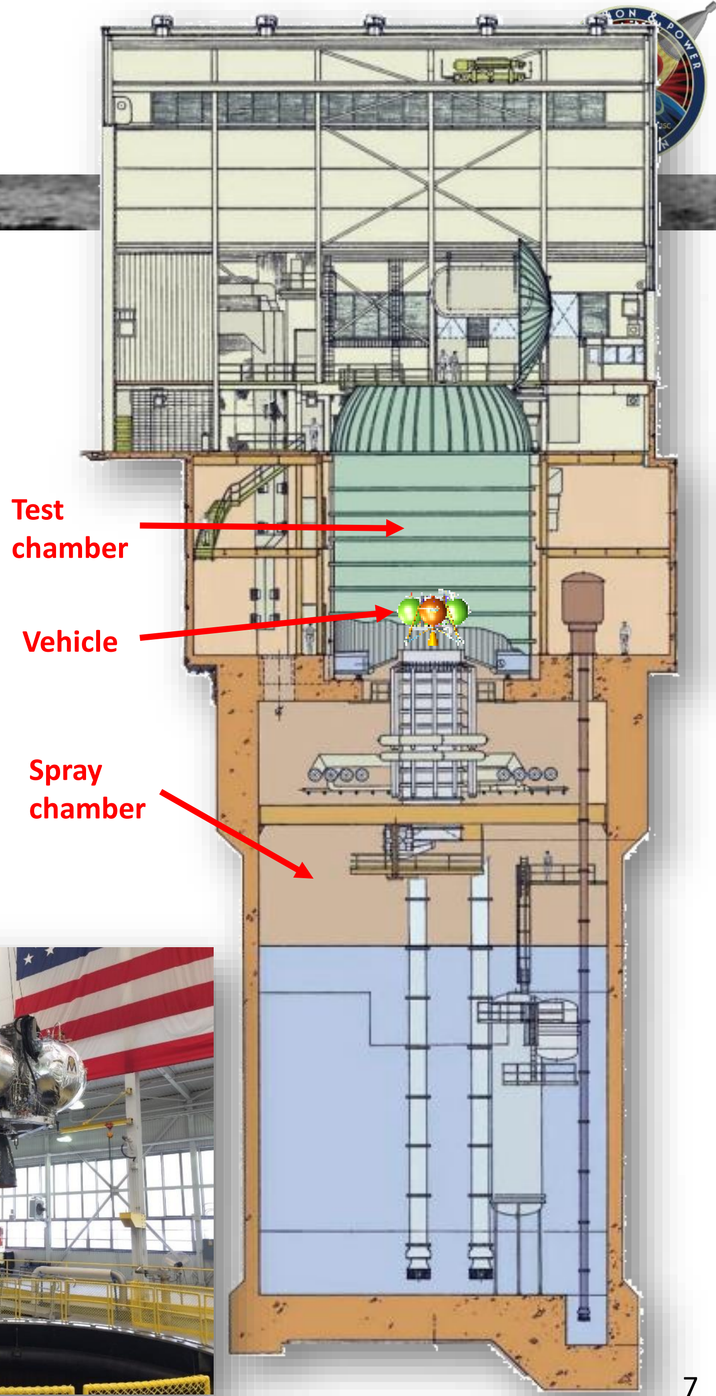


Plum Brook B-2 Facility Unique Key Features

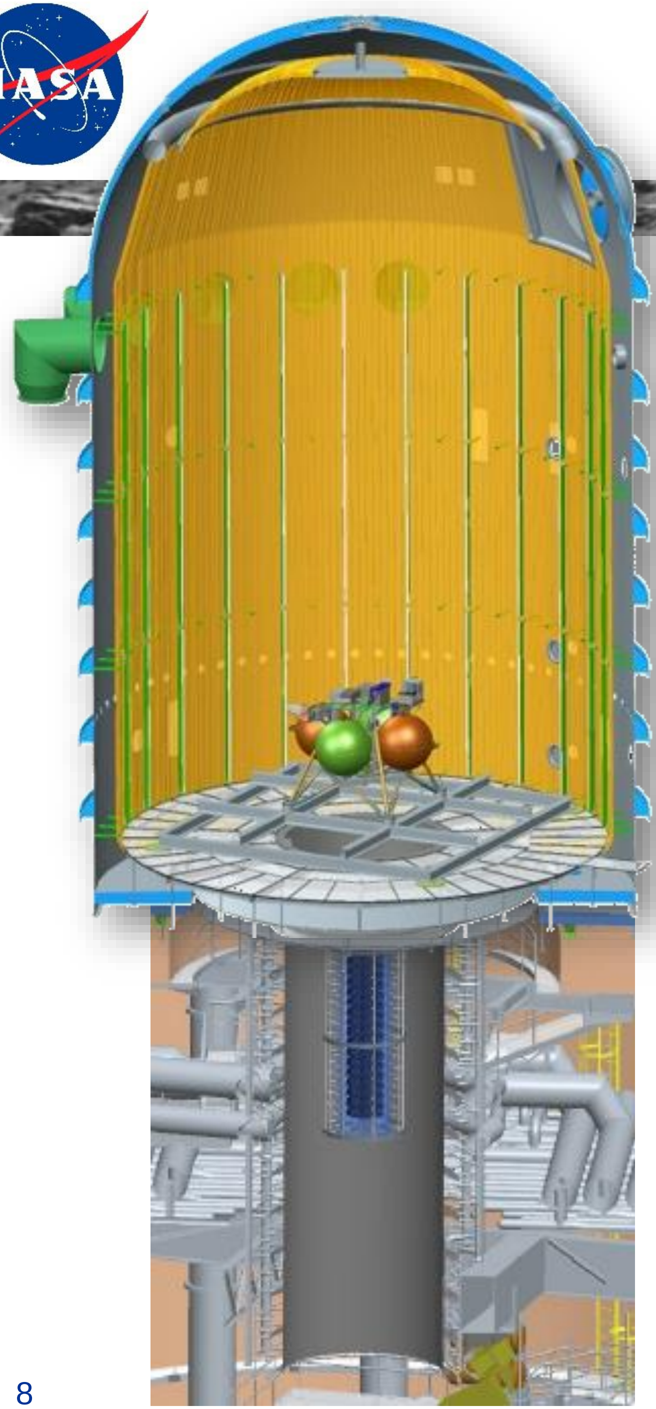
- **Provides real data on <u>integrated</u> systems operating in <u>relevant environments</u>**
- **World's largest (and NASA's only large) thermal vacuum propulsion test facility**
  - Allows full-scale vacuum/altitude testing of liquid fueled rocket engines, upper stages, and in space vehicles
  - Capable of long duration cold-soak and solar heating simulation
    - 80°K coldwall, thermal lamp array rotisserie heating (600 kW total).
    - Critical for on-orbit or interplanetary engine restart testing
  - Capable of engine hot-fire at 10 mbar (0.15psi) (100K ft altitude)
  - Tanking, thermal balance of upper stage/vehicle, propellant management
  - Facility has a very large exclusion zone (buffer area)
  - Remote control room

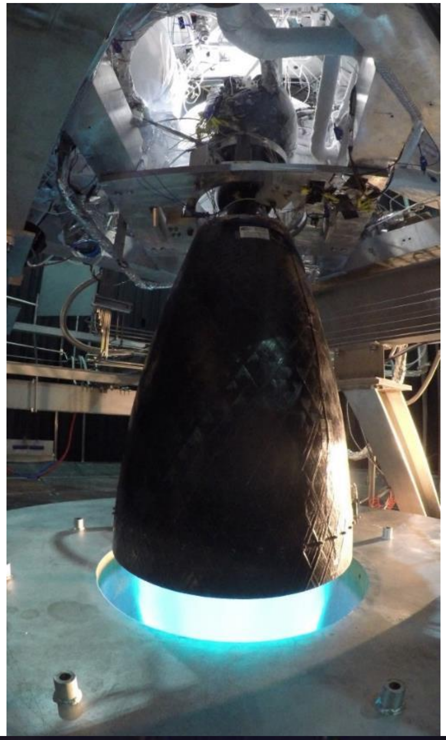
- **Facility was originally constructed to test the Centaur Upper Stage with RL10 engine(s) for up to 600 seconds.**
  - Baselined for 440 KN (100K LBF) thrust for 280 seconds.
  - 11ft Diffuser diameter sufficient for the large area ratio nozzle.

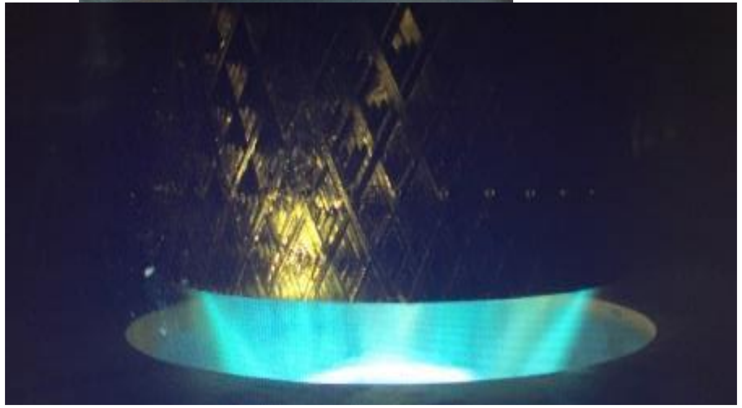




Diffuser Insert and Cooling



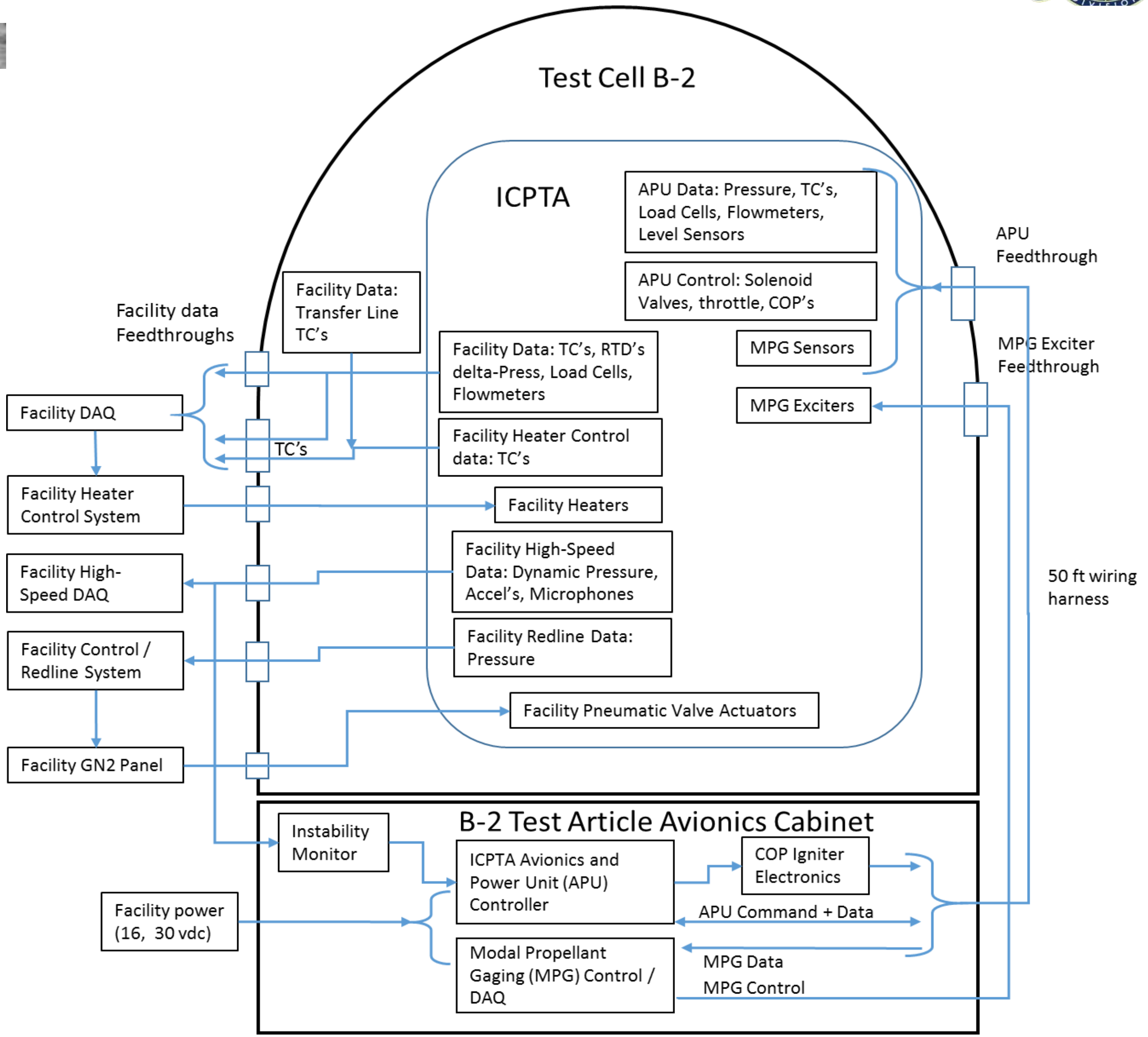




7000 gal water tank, feeds diffuser cooling spray bars.
Enters chamber through upper personnel door.

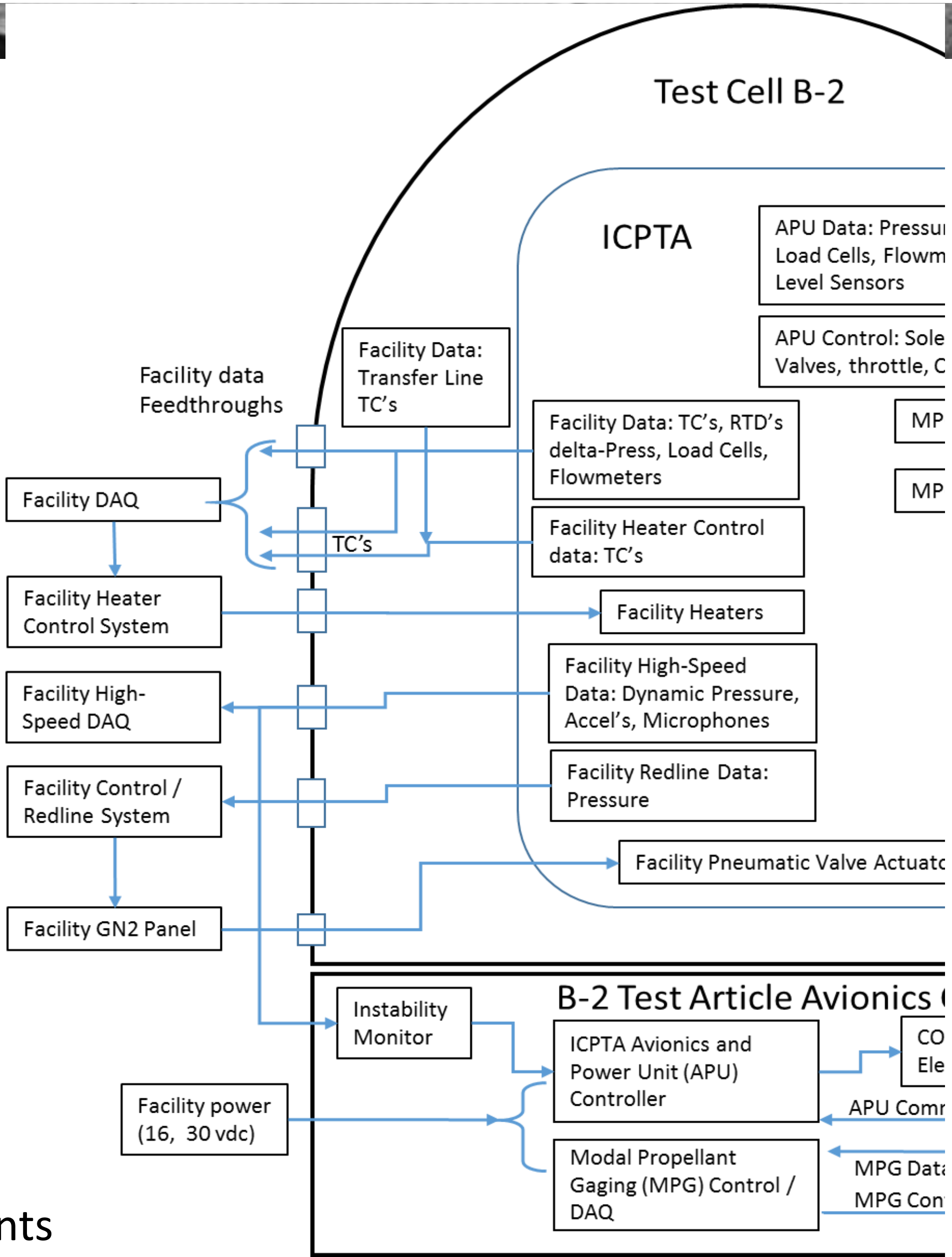
Control and Instrumentation Overview

- Primary Purpose of the test campaign was to collect system level performance and model validation data
- >320 sensors in static and dynamic measurements
  - Temperature, Pressure, Flow Rate, Fluid Level
  - Load cells, Strain
  - Accelerometers and Microphones
  - Modal Propellant Gauging
- ~25% recorded by ICPTA Avionics and Power Unit (APU), remainder recorded by facility DAQ or dedicated recorder
- ICPTA APU and Modal Propellant Gaging (MPG) DAQ co-located outside test cell in avionics cabinet
  - APU data, vehicle valve and ignition system power lines co-located in single bundle, no EMI issues



Facility Control / Instrumentation Overview

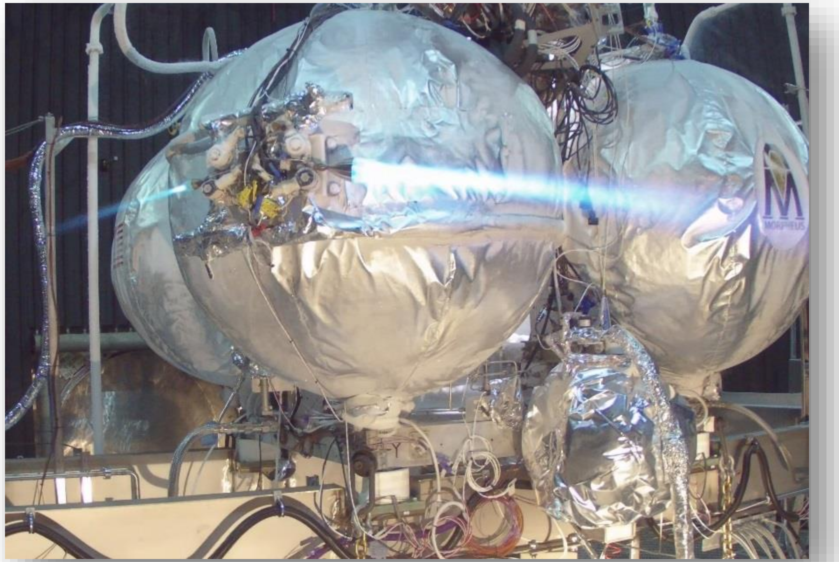
1) Data Recording system
   - 157 channels: Thermocouples, load cells, flowmeters, delta-press ducers, etc.
   - DAQ at 6.25 Hz (loading, chilling, etc.)
   - DAQ at 100 Hz (hot-fire, dynamic ops)
2) High-Speed Data Recording system
   - 26 channels: Dynamic pressures, accelerometers, mics
   - 25,000 samples/sec per channel
   - Used for RCS water hammer data and main stability
3) Heater control system
   - 39 channels of Type E thermocouples
   - Monitored in heater control loop for non-cryogenic rated hardware in cold-thermal testing (e.g., actuators)
   - 25 heaters in 6 command channels
4) Facility redline independent pressure transducers (4)
   - Propellant and helium tanks, Main Engine chamber pressure
   - Redline response: activate thrust termination system and tank vents



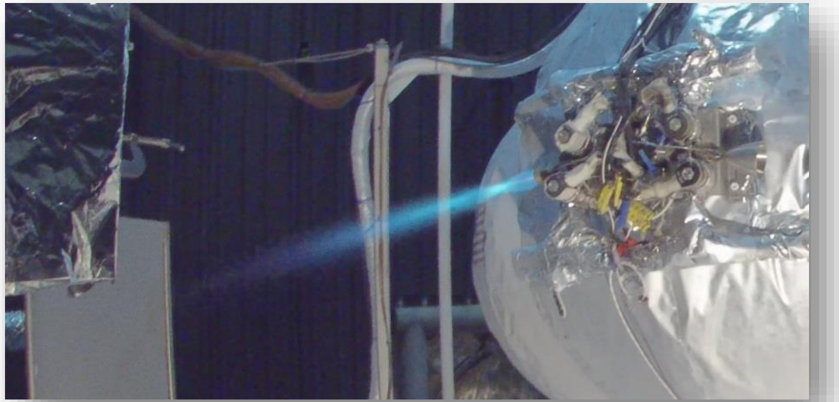
RCS Testing Overview

- First integrated cryogenic RCS demonstration in a thermal vacuum environment
- Major objectives:
  - Manifold priming dynamics
  - Manifold thermal conditioning in various heat leak environments (w/, w/o TVS)
  - Water hammer characterization
  - Main engine/RCS system interaction
  - Engine performance in cold soak environment
  - Coil-on-plug ignition system demonstration

- Test Summary:
  - 40 RCS tests with 1,010 ignition attempts with ~95% success
    - Transit phase MIB pulsing
    - Ascent/landing phase high duty cycle pulsing
    - Steady-state operation
  - Gas-gas, gas-liquid, and liquid-liquid inlet conditions
  - 7 ME+RCS simultaneous tests
  - Altitude conditions ranging from 0.01 to 30 torr
  - Temperature conditions ranging from ambient to -320 F cold wall
  - RCS manifold and engine instrumentation: 4 submerged TCs, 12 welded-on TCs, 16 stick-on TCs, 4 static PTs, 6 dynamic PTs



Mission duty cycle pulsing, Hotfire 4



Thermal-vacuum ignition of 7 lbf jet, Hotfire 6

ME Testing Overview

2,800 lbf vac LOX/Methane engine developed at NASA JSC

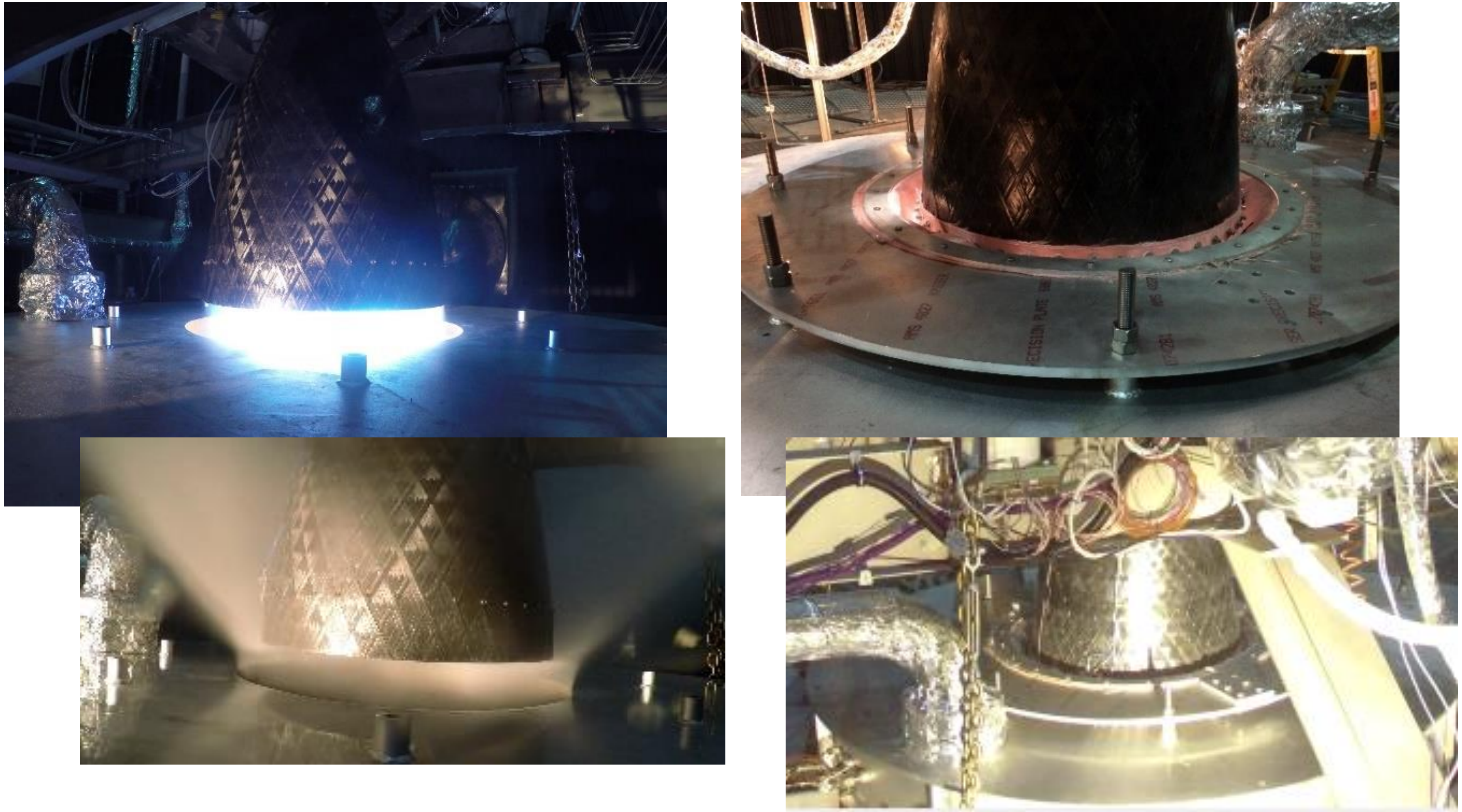
- 5:1 throttle ratio, 100:1 composite nozzle with integral HEX
- Thrust measurement system integrated into vehicle structure
- Spark torch ignition using coil-on-plug igniter

Main engine performance satisfied campaign prime objective

- Test campaign hotfire tests at Plum Brook
  - JSC2kb injector:
    - 12 starts, 60 sec total runtime, 27 sec longest test
    - @ JSC: 6 Starts, 17 sec total runtime, 6 sec longest test
  - JSC2ka injector
    - 7 starts, 97 sec total runtime, 55 sec longest test
    - Numerous other firings at JSC, SSC
- Tested with and without nozzle boot
  - Substantial water sprayback without boot
  - Short duration fire in test cell after long duration test using boot
    - Repress of methane rich air from spray chamber

Nozzle Boot Used to Mitigate Spray Chamber Blowback

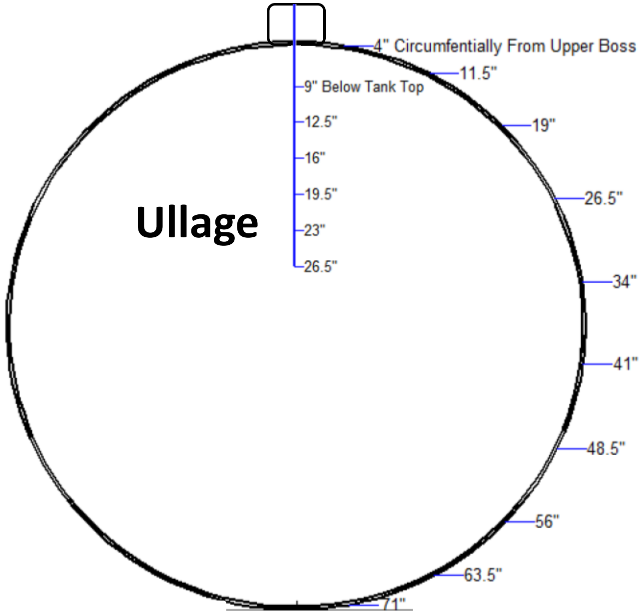
- Nextel fabric boot added to main engine nozzle/chamber floor interface to reduce speed of test cell repressurization
  - Test cell repressurization is sonic at nozzle/floor interface
  - Concern is damage to vehicle, nozzle
- Tests up to 27 sec performed with and without boot to gauge system effects
  - Elevated, no-boot position also facilitated high speed plume visualization
- Boot chokes flow into a radial thin disk, reducing mdot and diffuser duct velocity
  - Greatly reduces quantity of spray chamber water entrained in repress flow

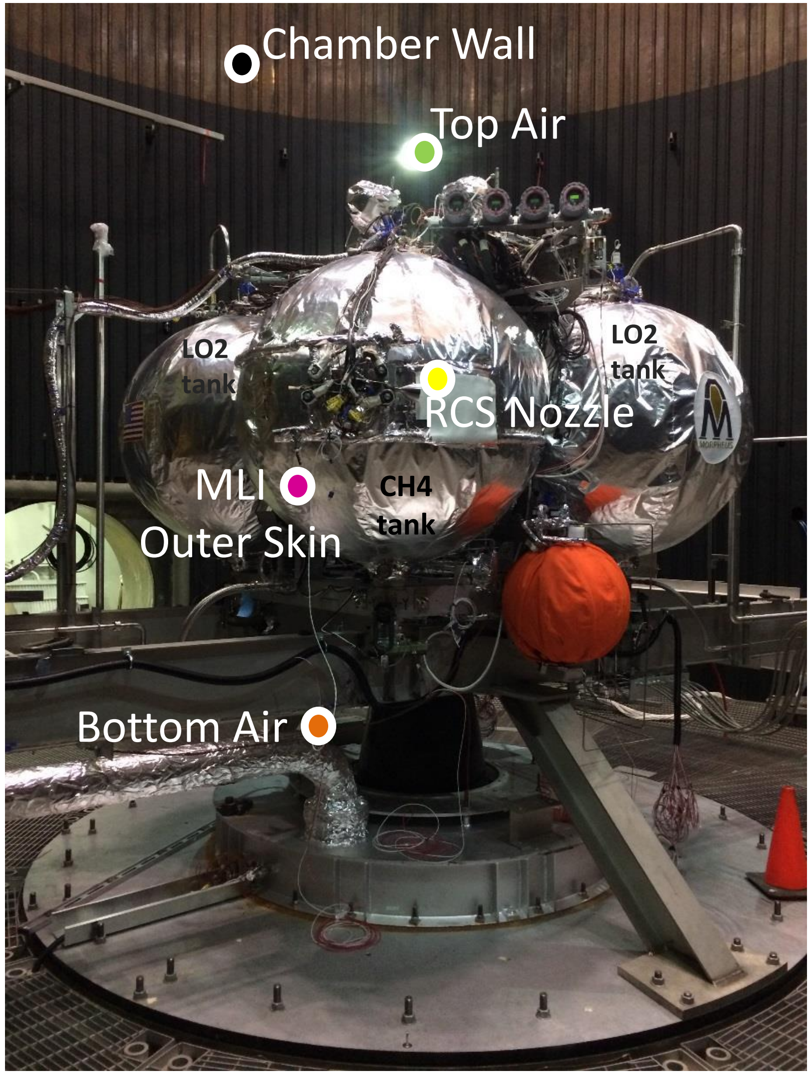


~20% reduction in nozzle tip vibration with boot

Thermal Sensor Overview

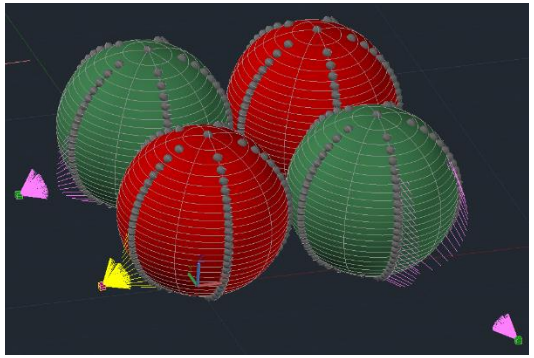
- Objective: Obtain thermal performance data and correlate with models
- Over 200 temperature sensors (Type T, K, E) on vehicle and in chamber
  - Chamber wall, air, tanks, feedlines, insulation, vehicle structure, RCS, ME
- LO_2 Tank (+/- Z) and CH_4 Tank (+/- Y) Instrumentation
  - 6 exposed thermocouples inside tank, suspended from upper boss top port
  - Skin thermocouples bonded to tank exterior

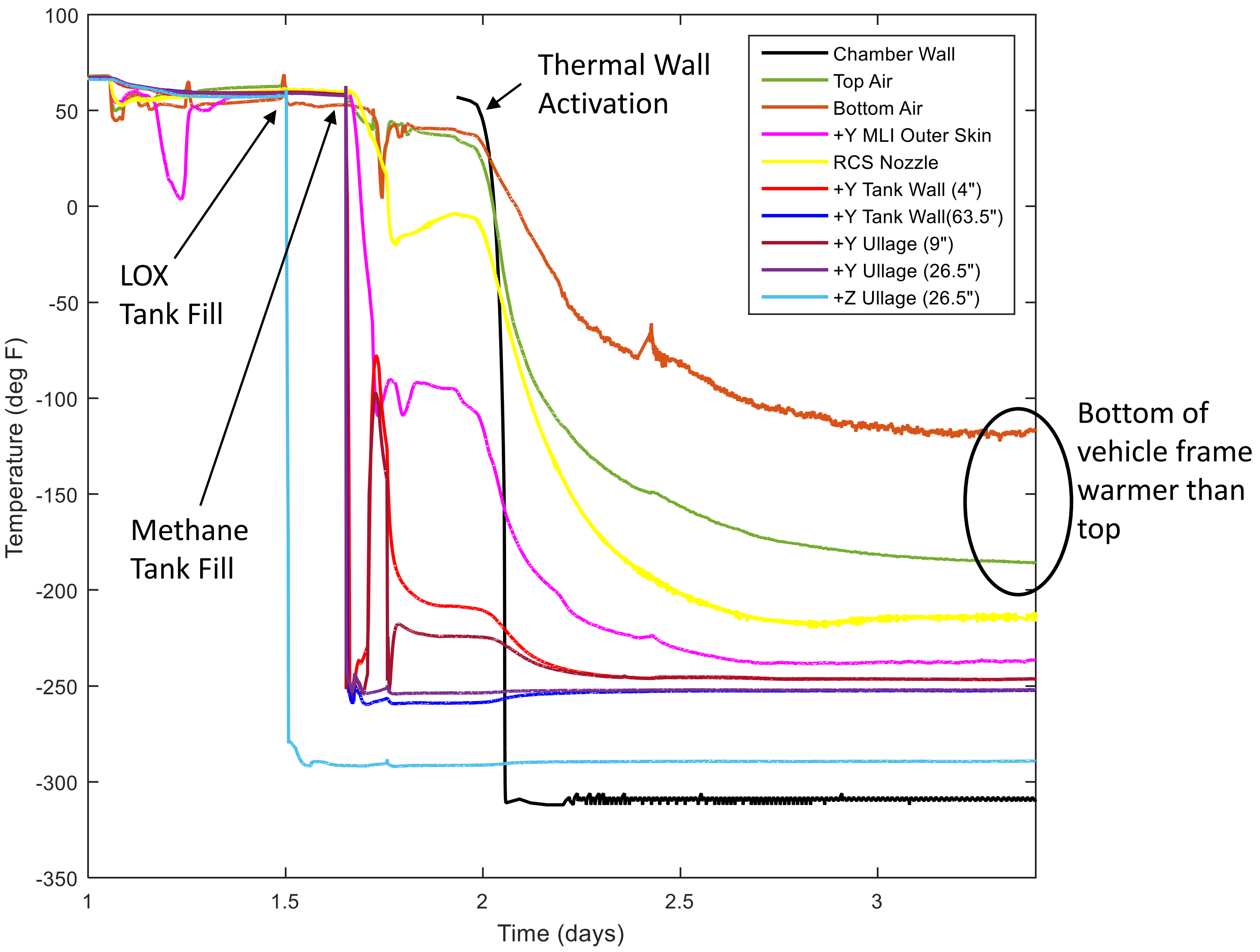




Vehicle Thermal Testing

- During the thermal vacuum test, propellants were loaded first followed by cold wall activation
- System steady state was reached about 1.5 days later
- Data collected during this test will be used to validate a Thermal Desktop model of ICPTA tanks, structure, and fluid line plumbing
  - Correlating effect of thermal chamber environment on vehicle temperature gradients

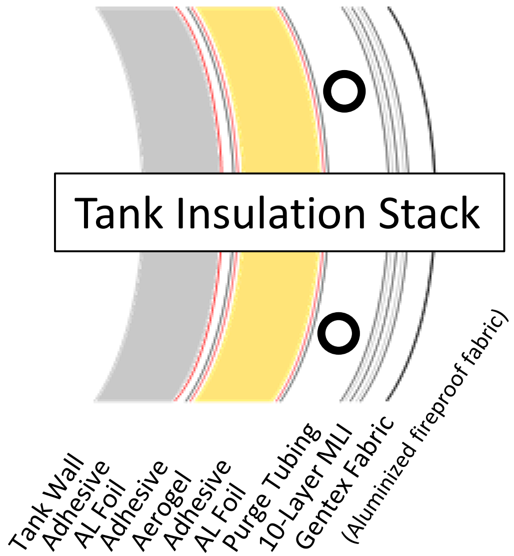




Insulation Scheme for Propellant Tanks and Propellant Manifolds

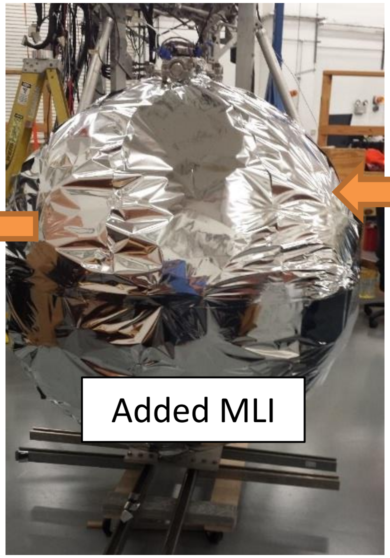
- Hybrid insulation system for the propellant tanks and propellant manifolds
  - 6mm aerogel layer with aluminum foil skin,
  - Perforated GN2 purge line for sea level operations
  - 9 layers of PET MLI (0.08% perforations)
    - Mercator map cut, bundled with minimal number of Monel staples, seams joined with MLI tape
  - Gentex aluminized fabric cover
- Provides effective insulation at both sea level and altitude conditions
- Thermal performance of insulation system tested down to 0.2 Torr


Bare tank with PZT sensors and cemented TCs



Tank Insulation Stack

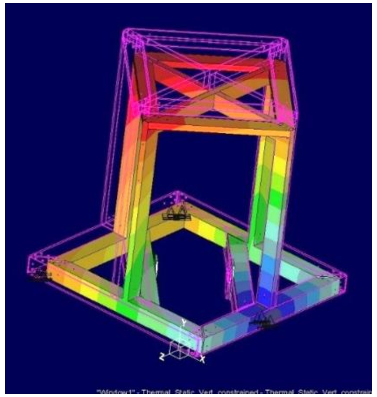

Final Insulation with Gentex Cover

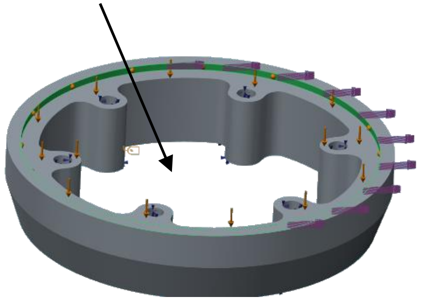

Added MLI

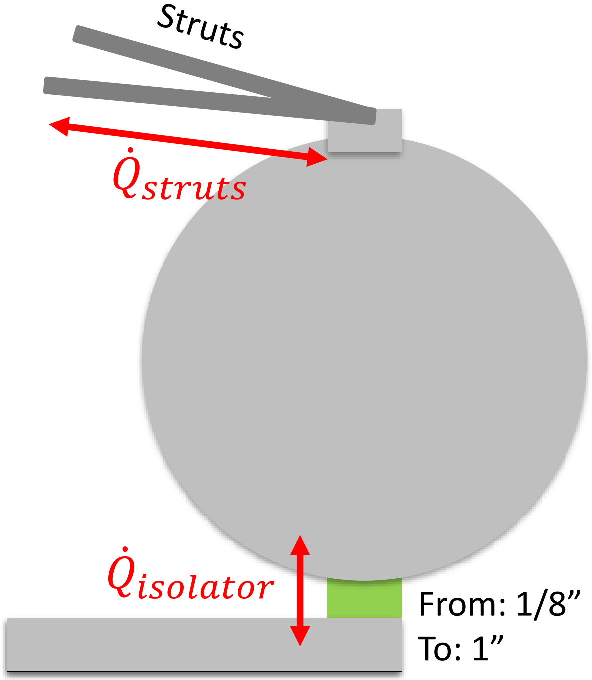

Tanks with foil covered aerogel blanket

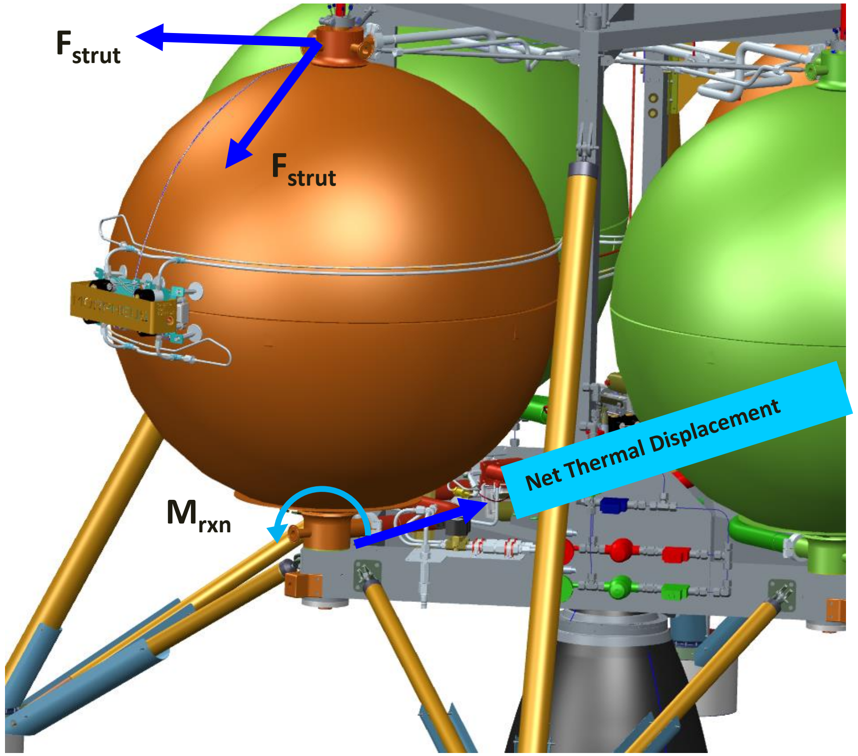
Propellant Tank Thermal Isolators

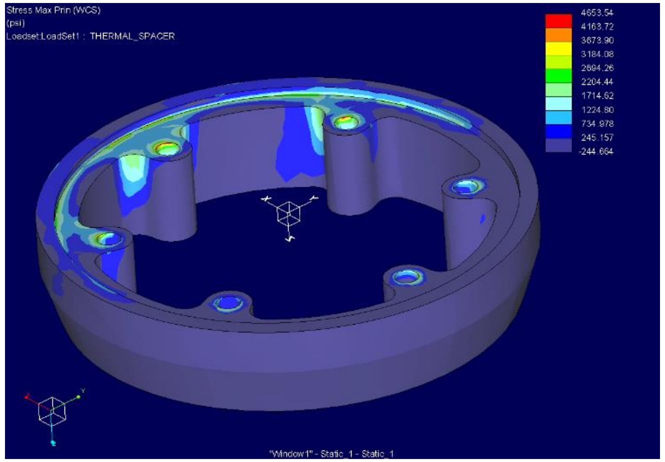
- Replaced tank/lower frame G10 spacers with 1” thick minimum surface contact spacer (originally 1/8”)
- Primary stress case: vehicle chill during thermal vac test resulting in tank rotation on thermal spacer
  - Upper struts and lower frame expected to chill at different speeds and also have different CTEs
  - New spacer built using axial fiber G10-FR4 fiberglass due to bending load (included MLI wafer between bolts)









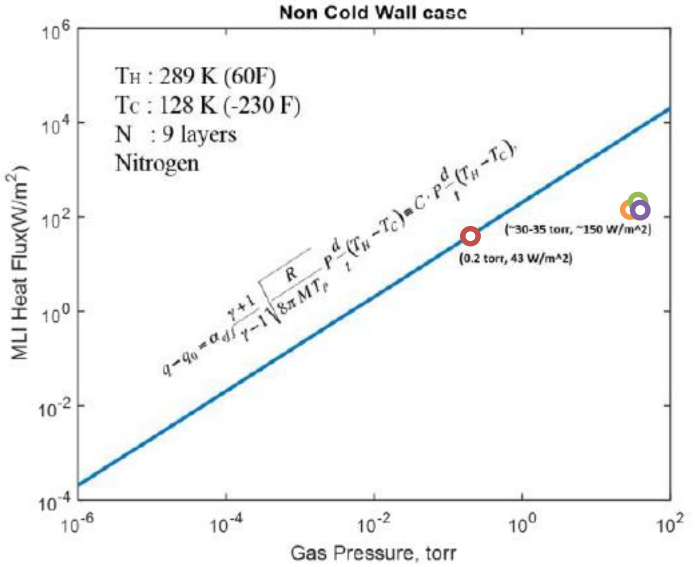


Stress due to tank bending load

Vehicle Boil-off and Heat Leak Data

ICPTA Propellant Tank Measured Heat Leaks

Test Location	Test	Conditions	LOX Boiloff after LOX Fill (lb/min)	Heat Leak per LOX tank (W)	Heat Leak per LOX tank (W/m^2)	Total Boiloff after LOX and LCH4 Fill (lb/min)
KSC	FF6	ambient, outdoors	-2.8	-2270	-485	**-5**
JSC	Cold Helium	ambient, outdoors	-1.9	-1540	-329	
Plumbrook	HF2	30 torr, no cold wall	-1.3	-1054	-225	-2.25
Plumbrook	HF3	35 torr, no cold wall	-0.9	-730	-156	-1.3
Plumbrook	HF4	35 torr, no cold wall	-0.7	-567	-121	-1.95
Plumbrook	HF5	30 torr, no cold wall	-0.85	-689	-147	-1.9
Plumbrook	HF6	0.2 torr, no cold wall	**-0.25**	-203	-43	-0.6
Plumbrook	HF6	0.3 torr, cold wall (-305 F)	**-0.15**	-122	-26	-0.25
	*In Red are estimated values					



Modified Lockheed-Martin MLI equation (non-cold wall case) against measured LOX heat leak values

RCS Oxygen Manifold Measured Heat Leaks

Test Conditions	Local Heat Leak (over 35" of line section)	Local Heat Flux	Estimated Total Heat Leak
Ambient	11 W	366 W/m^2	123 W
Cold Soak	1.4 W	46 W/m^2	15 W

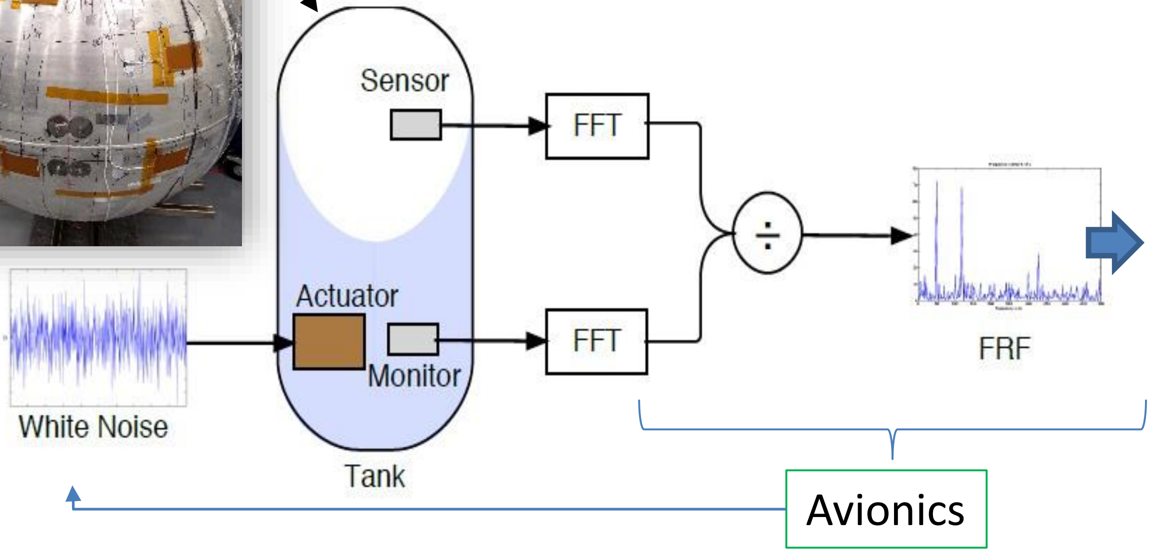
Overall Predicted Heat Leak into each propellant tank at 5E-6 Torr and 298K

Element	Heat Leak Per Tank	
	LO2	CH4
Tank Insulation	14.9 W	14.2 W
Structure	12.3 W	11.0 W
Propellant Lines	11.3 W	10.0 W
Total	38.5 W	35.2 W

Modal Propellant Gauge (MPG) Background

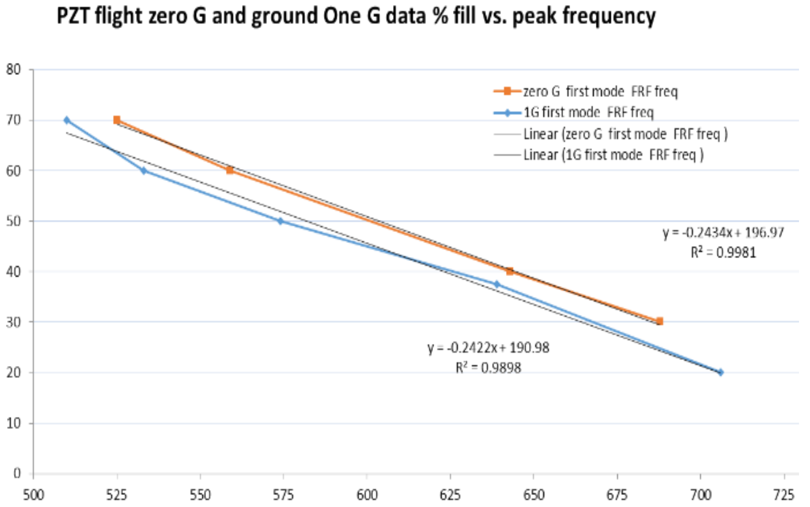
- MPG concept:
  - Numerous PZT patch sensors are adhered externally to a propellant tank.
  - One of these acts as an actuator, others as receiver sensors
  - Broadband white noise is introduced to the tank through the actuator.
  - A Frequency Response Function is computed from the FFTs derived from the sensor and monitor signals.
  - Mass in the tank is related to the FRF to with the capability to account for settled 1g and zero-g environments

PZT patches bonded
To LOX tank



Relate FRF to
Mass in tank

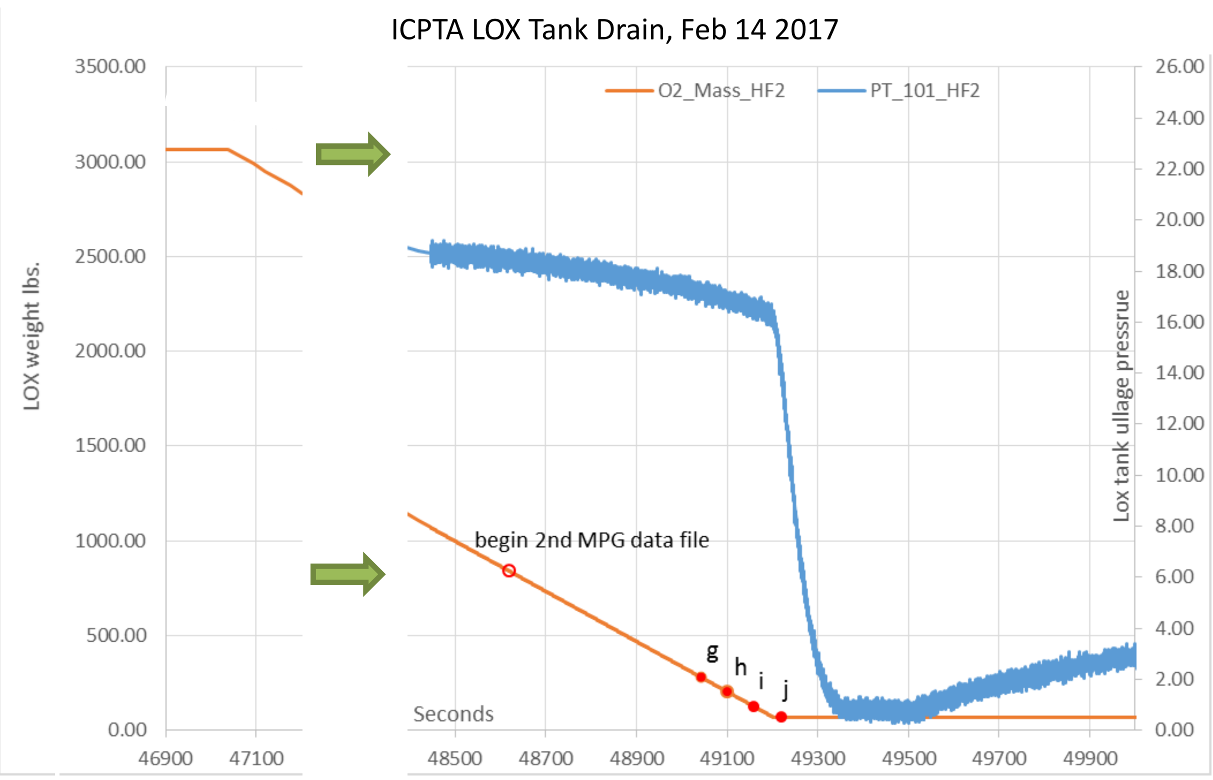
$$\text{Frequency} = \sqrt{\frac{K}{M}}$$

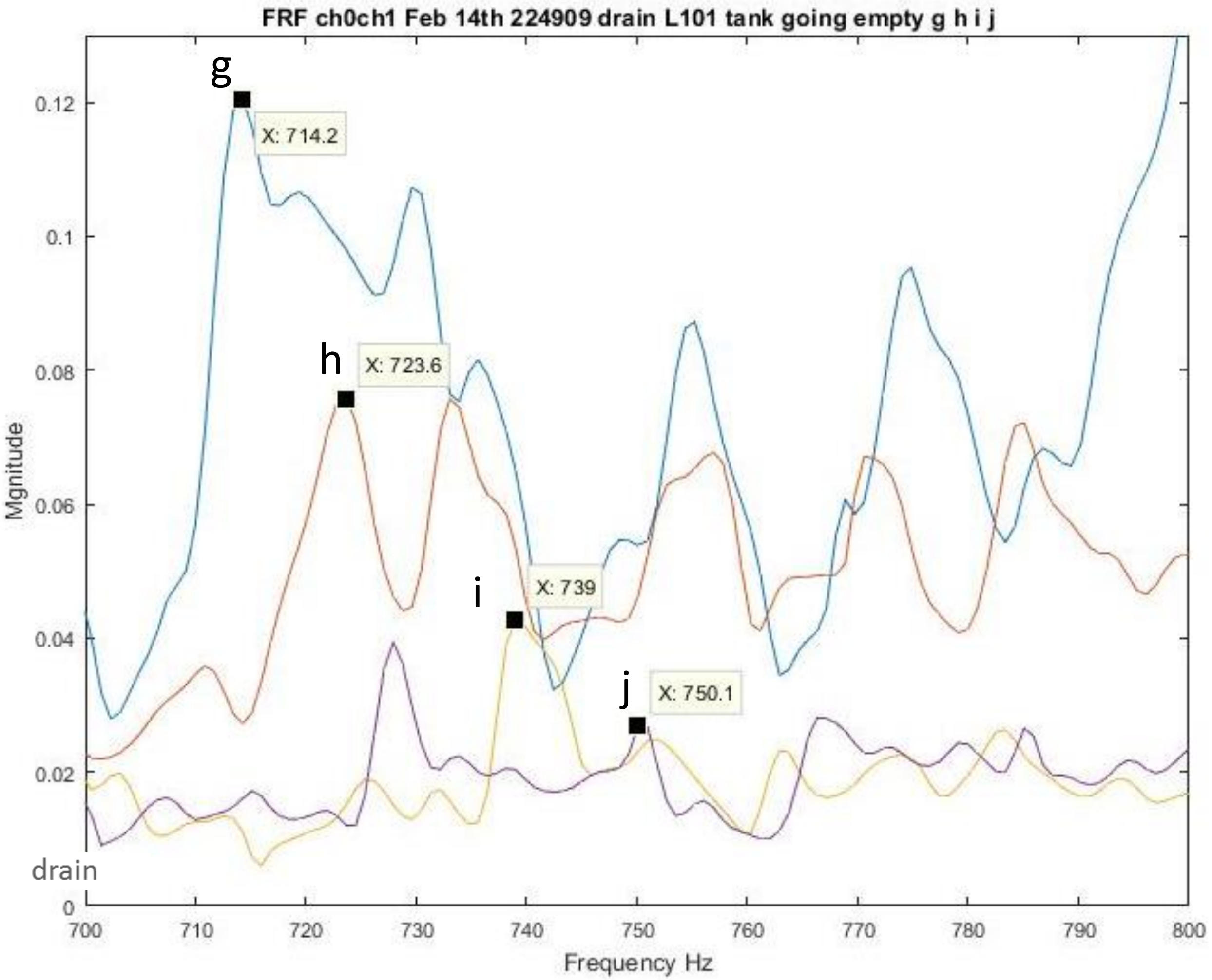


(PZT refers to the type of Piezoelectric sensor/actuator Pb[$Zr_x Ti_{1-x}$]O_3)

ICPTA LOX Tank Drain with Sample MPG FRF Data

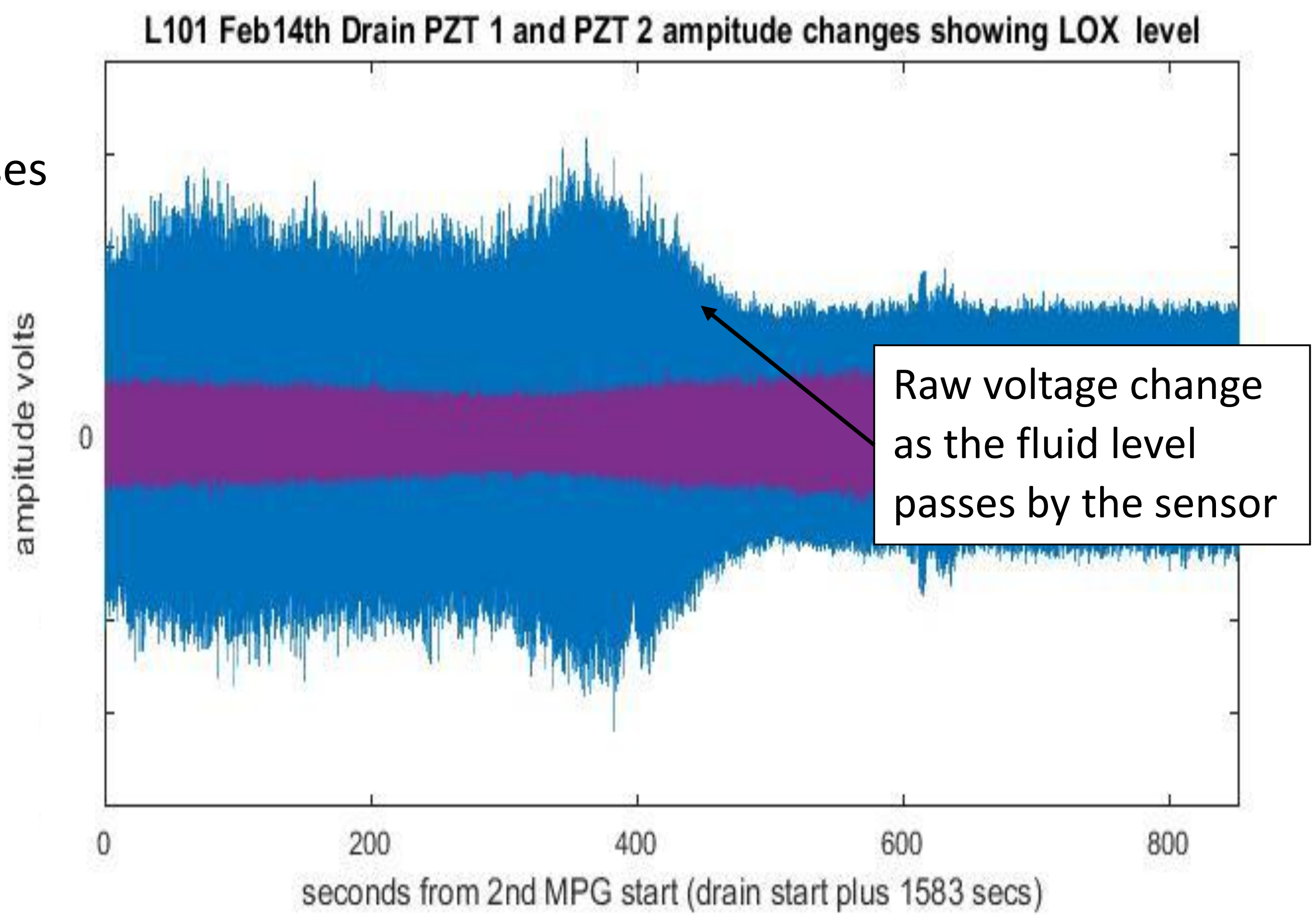
Example of MPG FRF data at 1 minute increments near the end of the tank drain event (g,h,i,j)





The MPG Sensor Can Also Be Used as a Propellant Level Sensor

- Amplitude of PZT sensor responses can indicate fluid level due to lower coupling without fluid interface
- The raw signal response rises and then decreases ~linearly as the fluid/gas interface passes the sensor
  - 2x4” typical sensor size



MPG System Status

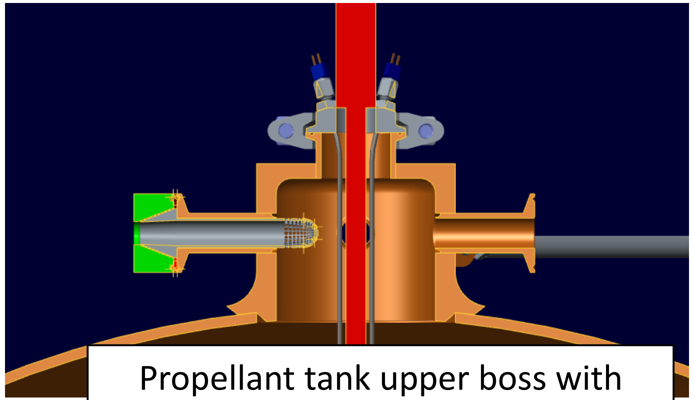
- MPG provides propellant mass gauging
  - Works in zero-g and settled conditions
  - Externally mounted and non–intrusive so it is compatible with all propellants including MMH/NTO
  - Detects quantity in each tank so it can be used for differential draining of parallel tanks and for leak detection over time
- Concept previously demonstrated statically, on vib tables, in zero-g flight
- Demonstrated performance using water and cryo fluids
- This experience was the first test under hotfire conditions
  - Support for experiment provided by NASA Orion program

- Since 2017
  - Performed fill and drain tests of Orion SM and OMS tanks
  - Created improved algorithms for tracking tank fluid mass independent of tank pressure
  - Preparing for system test using flight avionics

Cold Helium System Hardware

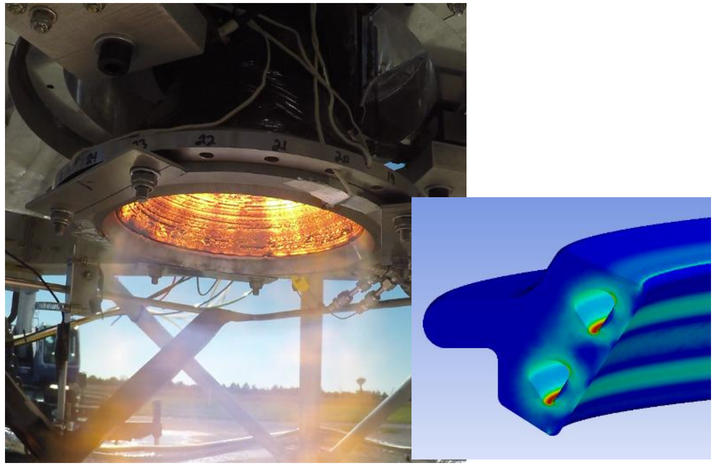
ICPTA utilizes a 19” spherical helium tank for propellant tank pressurization

- COPV is loaded with 3600 psi helium and chilled in-situ to below -250F
  - Sufficient for ~1 min main engine hotfires
- Propellant tanks are pre-loaded with facility helium
- Cryo helium flows through ME nozzle HEX at high pressure, then is regulated to tank pressure through independent regulators and distributed to each tank pair through flowmeters



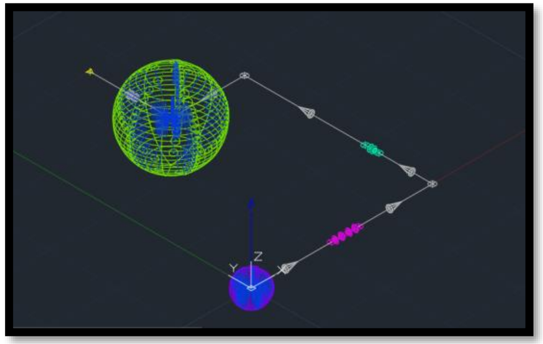
Propellant tank upper boss with helium diffuser shown

Diffuser insert

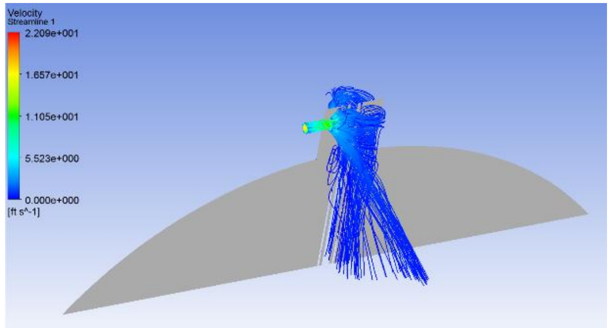


- Additively manufactured heat exchanger using Inconel 718 (sea-level testing configuration shown)
  - 3600 psi design
  - Integral hot wall thermocouples
  - Max wall temp ~1300F

Helium regulation panel with COTS and Shuttle era hardware



Working on coupled thermal-fluid system model for the helium pressurization System using SindaFluint and Thermal Desktop



Repress flowfield with diffuser

Cryogenic Helium Pressurization

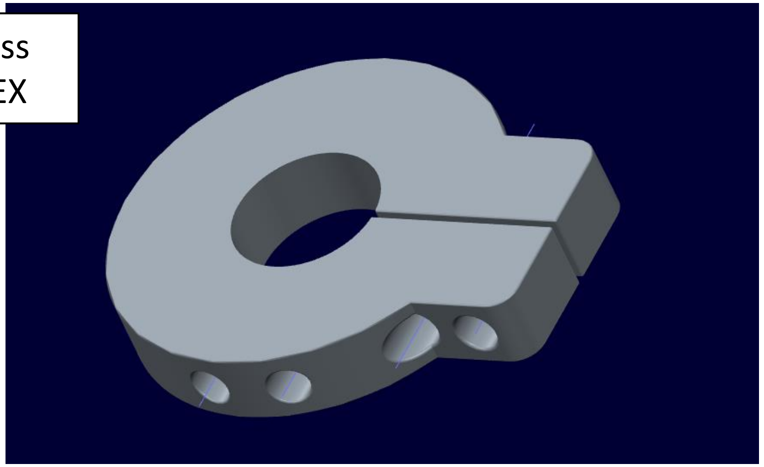
- Key objective: quantify effective collapse of helium pressurant due to heat transfer from incoming helium to cryogenic propellant, tanks, feedlines, etc
  - Instantaneous and cumulative collapse factors
  - $CF_i = \frac{\dot{m}_{Pressurant,\,actual}}{\dot{m}_{Pressurant,\,ideal}} \approx \frac{\dot{V}_{Pressurant}}{\dot{V}_{Propellant}}$ $\qquad CF_c = \frac{Total\ Mass_{Pressurant,\,actual}}{Total\ Mass_{Pressurant,\,ideal}}$
- In 2015, a dedicated cold helium hotfire experiment was performed on the same vehicle but using different HEX and helium system components
  - Propellant tanks ~20% full, ullage and vehicle hardware were relatively warm
  - CF_c ~1.0
- During the 2017 vacuum chamber experiment, the propellant tanks were >70% full for all main engine tests and helium system hardware was much colder than ambient
  - CF_i was measured between 1.2 and 1.9
  - For the 56 sec test, CF_c ~1.44
- The Main Engine was not operated at deep thermal conditions so the very high CF case was not measured
  - Data collected will be used to validate system models that will predict this worst case CF

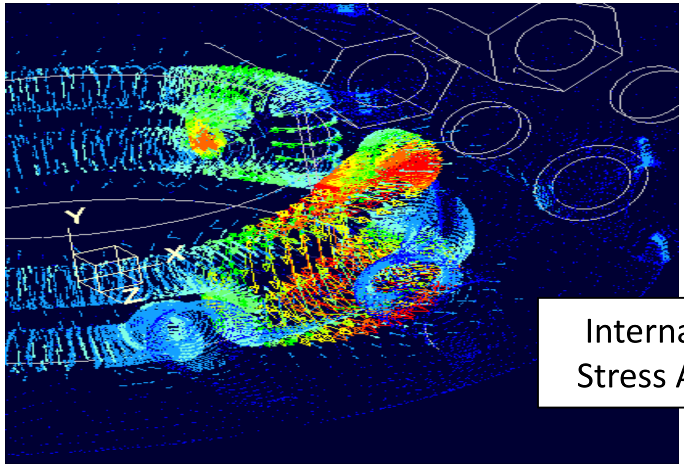
Cryo Helium COPV Loading Optimization Study

Data analysis in work

- Helium tank hardware was improved from the 2015 cold helium experiment to improve system performance and make more flight-like
  - Replaced previous Inconel-lined COPV with Aluminum version (same specs, vendor, SBIR)
  - Replaced aluminum COPV support structure with G-10 fiberglass to reduce heat transfer
  - Replaced aluminum tank collar interface bracket with UHMW plastic version to reduce heat transfer
  - Replaced aerogel blanket with original vacuum compatible foam insulation (SBIR)
    - Overwrapped in MLI blanket similar to propellant tanks
  - Installed LN2 dump cooling path under insulation
  - Added closed-loop LN2 expansion heat exchanger collars to both tank bosses
    - 3D printed aluminum double-pass HEX
    - LN2 flow path: solenoid control valve, expansion orifice, top collar HEX, tubing, bottom collar HEX, then back to facility

COPV Boss Collar HEX

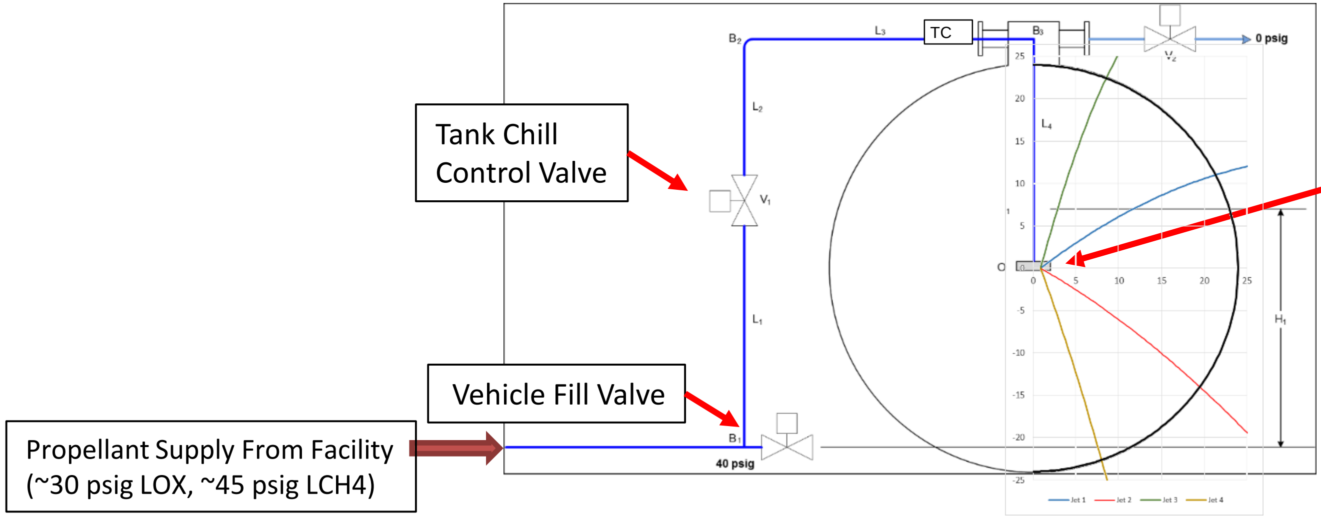




Internal Passages Stress Assessment

Additional Heat Transfer Experiments

- Methane Fill Line Heat Transfer
  - Collected propellant transfer line quench/chill data for liquid methane and liquid oxygen
  - GRC research goal: determine heat transfer characteristics under controlled conditions
- Methane tank internal spray-chill system
  - 360[2] spherical spray “doughnut” installed in one methane and one oxygen tank to collect heat transfer data on internal chilling (tank vented to ambient pressure)
    - Methane tank effectively chilled internally with subcooled propellants
    - Facility transfer system could not maintain subcooled oxygen at low spray doughnut mass flow rate



Spray Doughnut
Anchored to
Capacitance Probe

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- ICPTA vehicle development funded by NASA JSC Engineering Directorate, Laurie Hansen, Director.
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- COP and RCS component development and testing at JSC funded by NASA JSC Engineering Directorate, Propulsion and Power Division, Edgar Castro, Chief.
- Many engineers and support staff at Plum Brook, GRC, SSC, and JSC

Vehicle currently on display at Space Center Houston

Other relevant papers for 2017:

"Characterization of Pressure-Fed LOX/LCH4 Reaction Control System Under Simulated Altitude and Thermal Vacuum Conditions," AIAA-2017-4668

"Coil-On-Plug Ignition for Oxygen/Methane Liquid Rocket Engines in Thermal-Vacuum Environments," AIAA-2017-4666