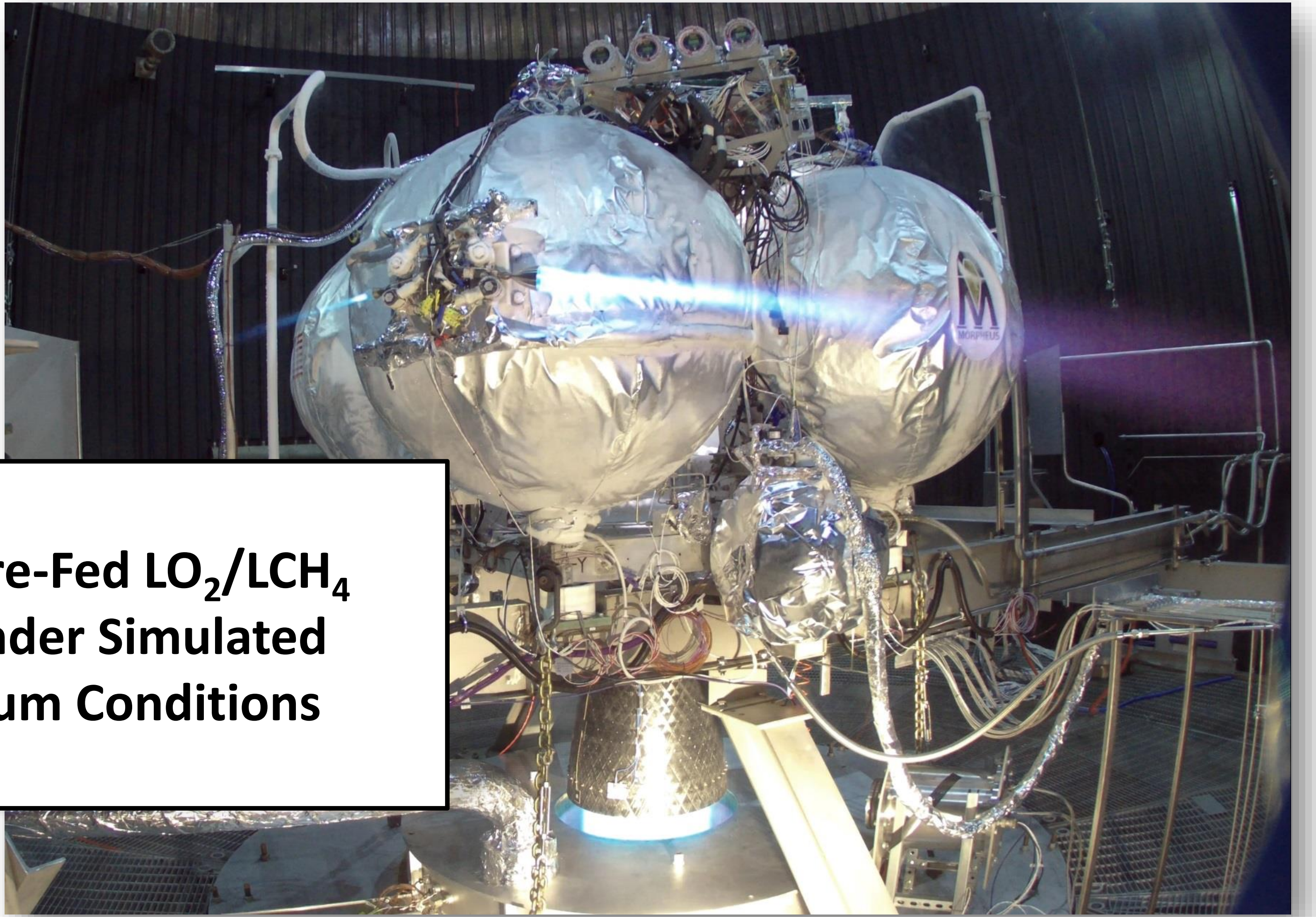
53rd AIAA/SAE/ASEE Joint Propulsion Conference

Atlanta, GA

July 10-12, 2017

Characterization of a Pressure-Fed LO_2/LCH_4 Reaction Control System Under Simulated Altitude and Thermal Vacuum Conditions



ICPTA altitude test, 2/28/17

Matthew Atwell, J.C. Melcher, Eric Hurlbert, Robert Morehead
NASA Johnson Space Center, Houston, TX

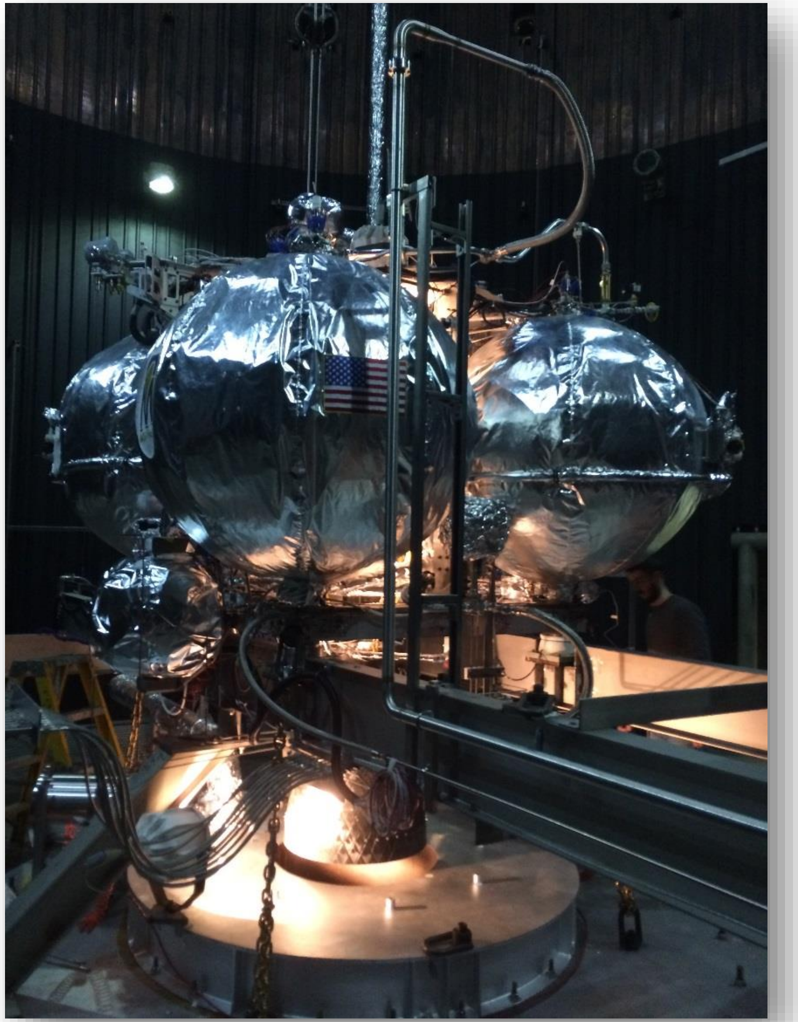
Executive Summary

- A pressure-fed LO_2/LCH_4 Reaction Control System (RCS) was tested as part of the Integrated Cryogenic Propulsion Test Article (ICPTA) at NASA GRC Plum Brook Station in the Spacecraft Propulsion Research Facility (B-2)
- 40 tests were performed with 1,010 individual RCE pulses across a range of conditions
  - Simulated altitude (ambient temperature, approximately 30 torr)
  - Thermal vacuum (-320 °F cold wall, 6 torr)
- Transient fluid dynamic data was obtained for RCE operation and priming using dynamic pressure transducers in the manifolds
- Transient thermal data was obtained for various operating regimes using a suite of skin-mounted and submerged thermocouples
- Data obtained will be used to anchor thermal/fluid models with specific emphasis on validating a water hammer model to predict valve opening and closing transients
- Demonstrated RCS engine ignition and system operation over a wide range
  - Gas-gas operation
  - Two-phase (self-conditioning) and liquid-liquid operation
  - Ignition issues at thruster body temperatures less than -160 °F -> may require thruster heater unless design is improved

IPCTA on the way into B-2

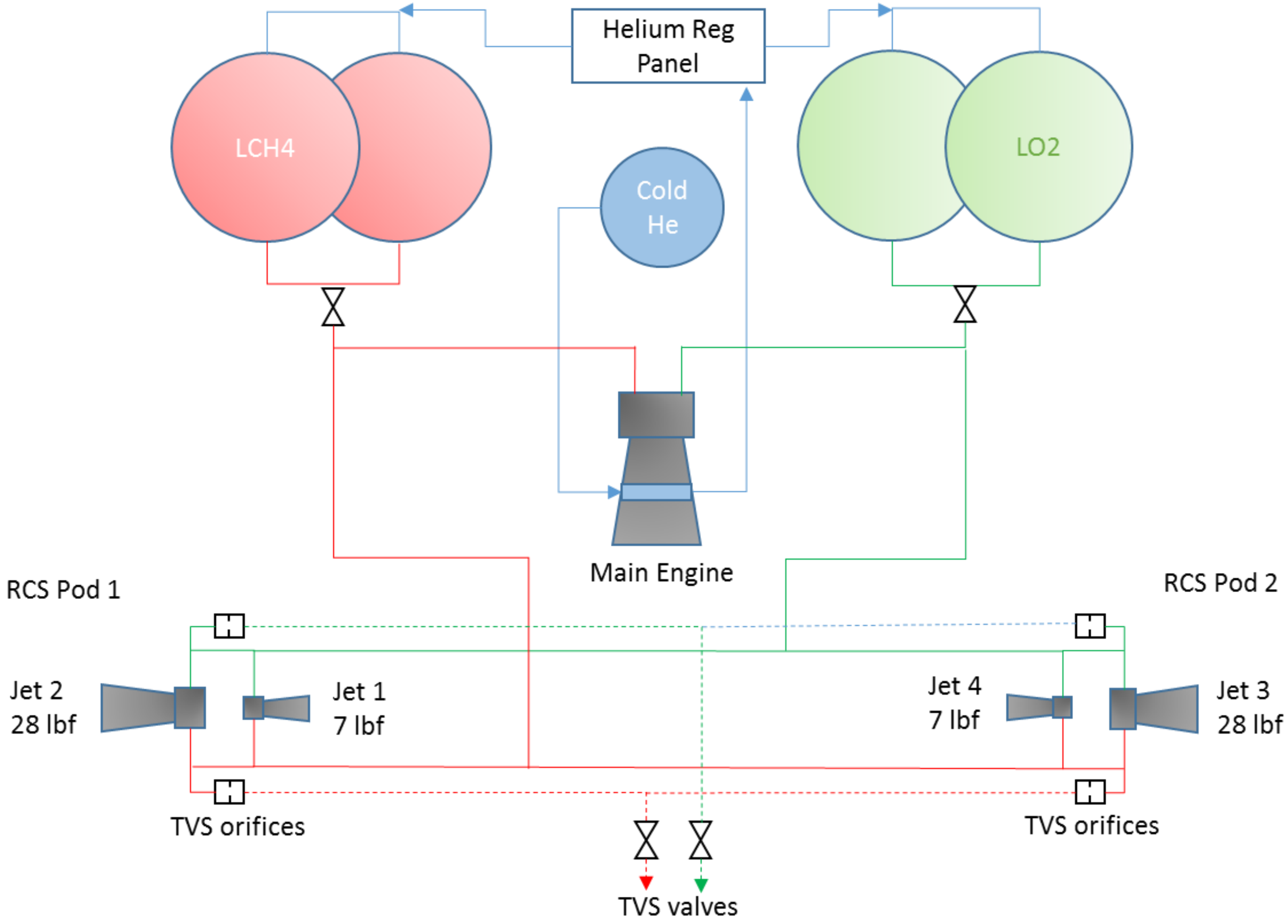
ICPTA Overview

- Integrated Cryogenic Propulsion Test Article (ICPTA) propulsion elements:
  - Four 48” diameter 5083 aluminum propellant tanks (two per commodity) with integral slosh baffles
  - Tanks and feedlines insulated by 6mm layer of Pyrogel XT, surrounded by 9 layers of MLI consisting of 1 mil polyester film (PET) radiation barrier and 2 layers of polyester B4A netting spacers
  - 2,800 lbf-thrust pressure-fed main engine
  - Reaction control system with 4 engines (roll control)
  - Pressurization system composed of cryogenic high pressure helium stored in 19” Al-lined COPV, heated by engine-mounted heat exchanger before propellant tanks
- Add-on hardware for Plum Brook testing included: Propellant Mass Gauging experiment, tank chill experiment
- Leverages propulsion system hardware from Project Morpheus (2011-2014): same vehicle structure, propellant tanks, feed system, avionics, flight computer
  - Additional modifications made for thermal vacuum environment (100:1 nozzle extension, APU moved outside of test cell, new wiring, etc.)
  - Over 320 sensors to measure temperature, pressure, flow rate, force and strain data (most added for this test)



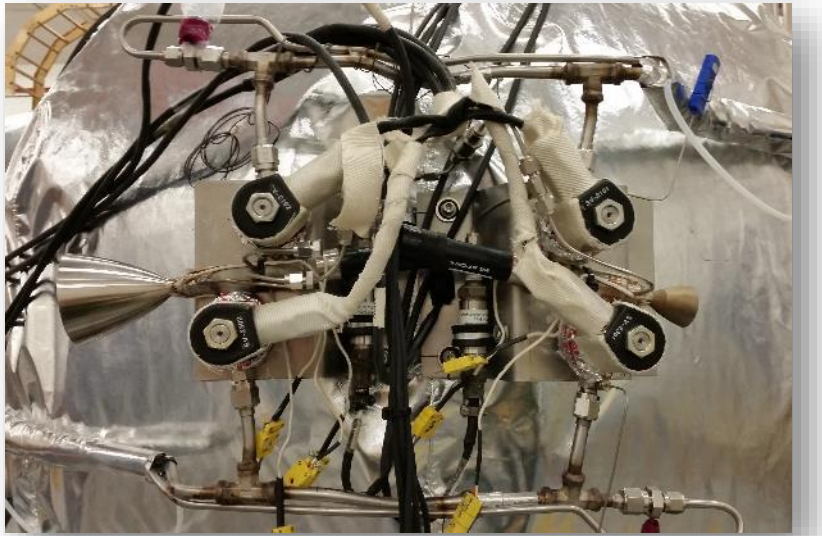
ICPTA integrated in B-2 facility

ICPTA Schematic

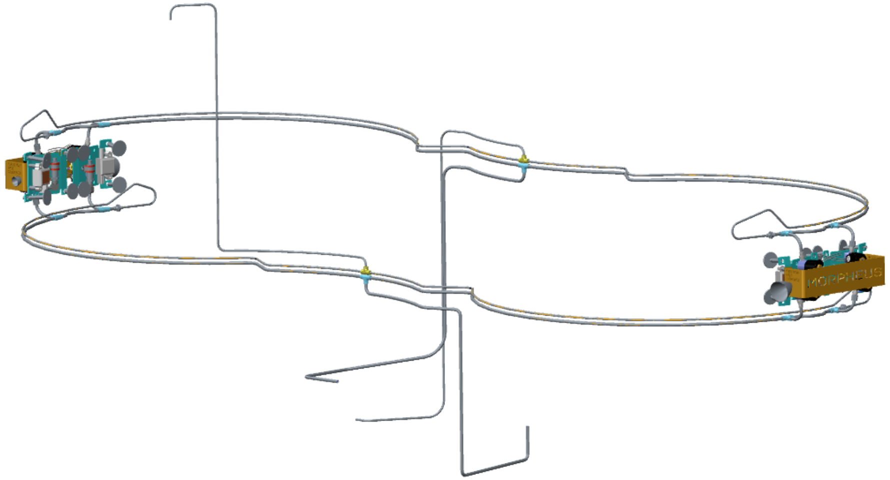


RCS Design

- One 7 lbf-thrust and one 28 lbf-thrust engine are located outboard of each LCH4 tank (4 engines total)
  - 28 lbf-thrust (vacuum) RCE is heritage Morpheus hardware with new vacuum nozzle
  - 7 lbf-thrust (vacuum) RCE is sized for Morpheus-based lander application in space (no high aero-torques)
  - Engines are designed to handle wide range of propellant inlet conditions from gas-gas (short duration) to liquid-liquid (steady-state) over a wide range of pressures (350 psig down to 150 psig)
- Common feed system with main engine
  - RCS manifolds tap off from main engine feedline downstream of isolation valves
- TVS is used to chill-in manifolds and engine pods
  - J-T expansion orifice with cold vented products routed through tubing that is welded to RCS manifold to efficiently reject heat
- Coil-on-plug ignition system
  - Developed from off-the-shelf automotive hardware
  - Vacuum potted; inductive discharge coils
  - No high-voltage lead, preventing corona discharge issues



RCS pod with one 28 lbf RCE (left) and one 7lbf RCE (right) uninsulated

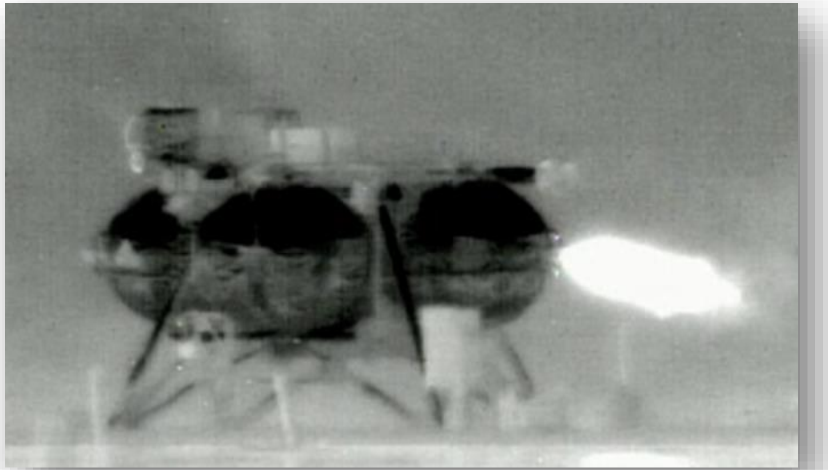


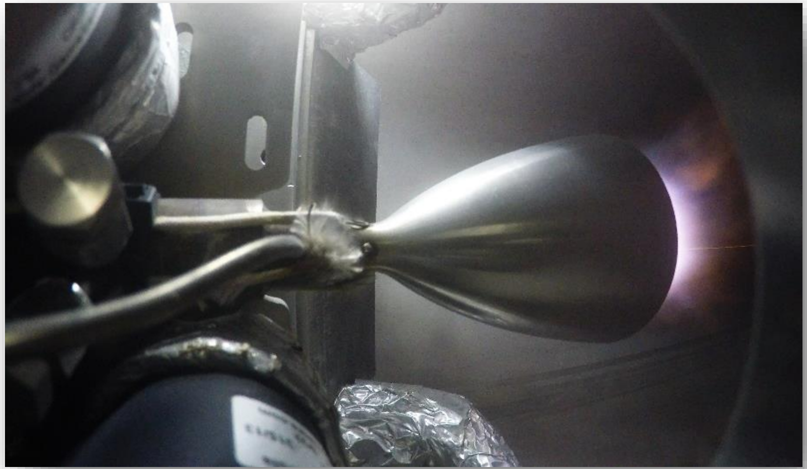
RCS feed line layout

Summary of Previous RCS Testing

- 5,300+ individual RCE ignitions during Project Morpheus
- Development testing occurred on CryoCart, a JSC asset capable of running LO_2/LCH_4 engines less than 100 lbf
  - 2012-2013 development cycle: 1,641 ignitions in 1,895 attempts
- Morpheus 1.5B free-flight testing: 1,299 ignitions in 1,306 attempts
  - 3,713 ignitions in 4,276 attempts across all vehicle development tests
  - Fleet leader had 1,134 successful ignitions
- Additional CryoCart testing was performed prior to Plum Brook, utilizing a vacuum pipe to allow for qualification testing of new coil-on-plug igniter hardware and vacuum nozzles
  - Ignition was demonstrated in ambient pressure conditions from 50 torr to 0.03 torr

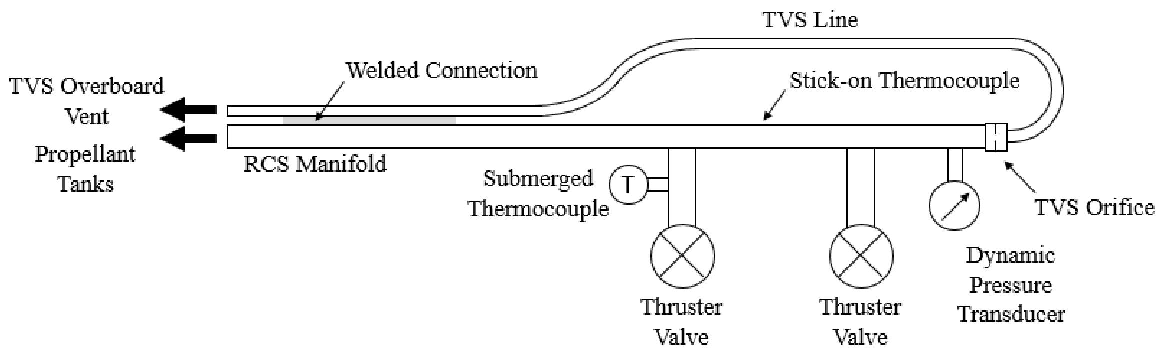

CryoCart development testing during Project Morpheus


IR imagery showing RCE firing on Morpheus vehicle


Vacuum pipe ignition demonstration on CryoCart

Test Overview/Instrumentation

- Major objectives for Plum Brook RCS testing included:
  - Manifold priming dynamics
  - Manifold thermal conditioning
  - Water hammer characterization
  - Main engine/RCS system interaction
  - TVS performance
  - Engine performance in cold-thermal environment
  - Coil-on-plug ignition system demonstration



RCS pod sensor locations

- 40 tests were performed consisting of 1,010 individual RCE pulses across a range of duty cycles and propellant conditions
  - 864 pulses under simulated altitude (ambient-thermal) conditions in the 20-50 torr range
  - 23 pulses under thermal vacuum conditions at approximately 6 torr with the cold wall at -320 °F
  - MIB pulsing (coast mission phase), high duty cycle pulsing (ascent/landing mission phase), and steady-state operation
  - Gas-gas, saturated/gas-liquid, and liquid-liquid inlet conditions
  - 7 ME+RCS simultaneous tests
- RCS instrumentation:

Type:	Submerged TC	Weld-on TC	Stick-on TC	Static PT	Dynamic PT
Number:	4	12	16	4	6
Model:	Omega Type-T	Omega Type-K	Omega Type-T	Omega PX-309	Kulite CTL-190
Location(s):	RCE inlets	RCE nozzle throat	Various manifold locations	RCE Chamber	Manifold tap-off and pods

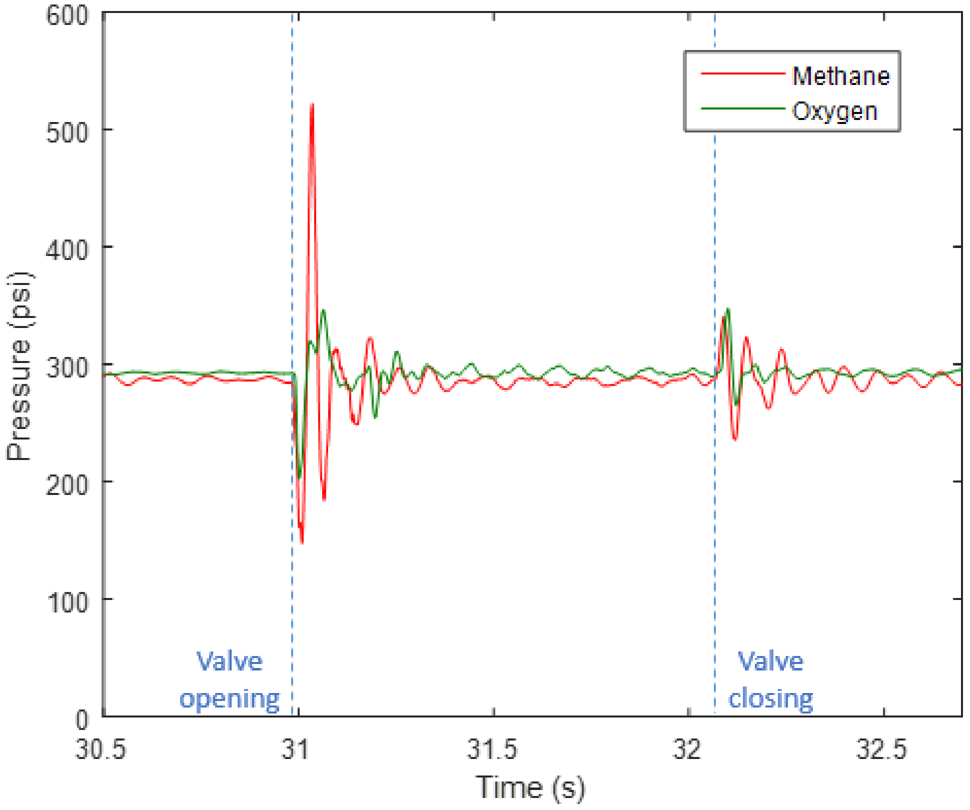
Test Video

Fluid Transients: RCE Operation

- Transient response was measured using dynamic pressure transducers for various thruster operation scenarios:
  - Gaseous/saturated propellant conditions in thruster manifold
  - Chilled-in manifolds during (ambient-thermal and cold soak testing)
- It was found that in general, the valve opening transient created a larger follow-on pressure peak than the valve closing transient
- Valve closing peaks were best characterized by engine shutdown after steady-state operation when the engines had fully chilled-in
  - Pressure peak amplitude for a 5 second test on each engine:

	Jet 1 (7 lbf)	Jet 2 (28 lbf)	Jet 3 (28 lbf)	Jet 4 (7 lbf)	28 lbf prediction	7 lbf prediction
Oxygen	18 psid	79 psid	91 psid	23 psid	72 psid	20 psid
Methane	33 psid	115 psid	97 psid	24 psid	140 psid	35 psid

  - This data agrees with Joukousky prediction for pressure surge (based on instantaneous valve closure and compressible fluid), within measurement uncertainty

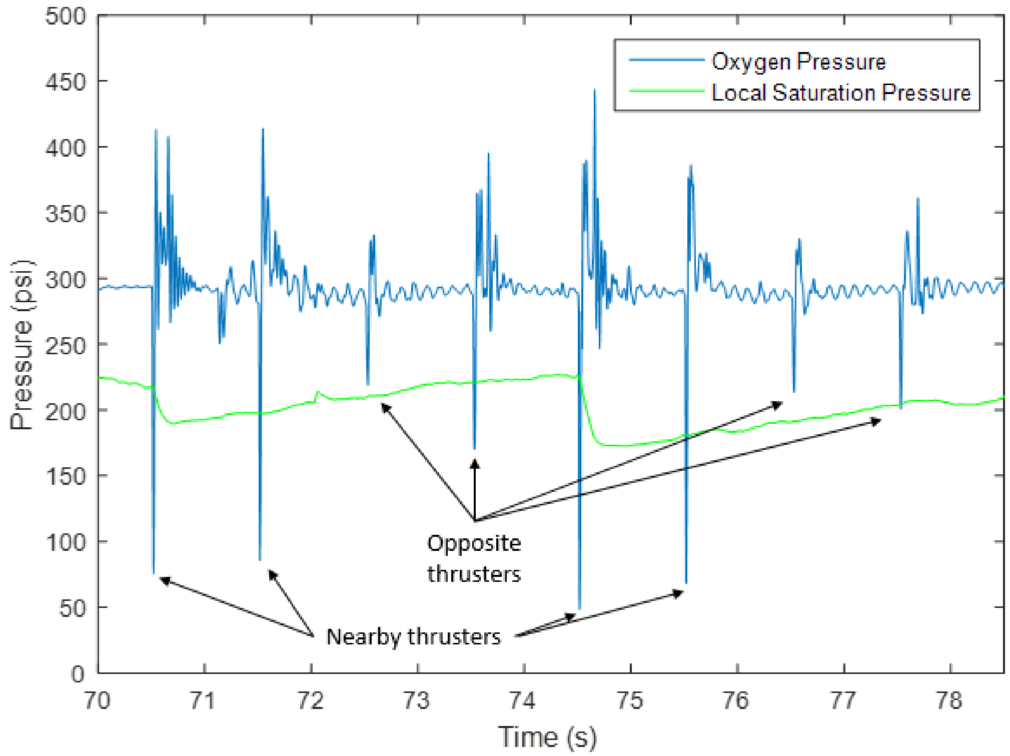


Typical water hammer for 0.5 second pulse

- Valve closing peaks during shorter pulses or saturated propellant operation showed more variability due to secondary interactions, but were typically lower in magnitude
- High peak pressure amplitudes were observed during cold-thermal testing, likely as a result of the less compliant fluid environment

Fluid Transients: RCE Operations

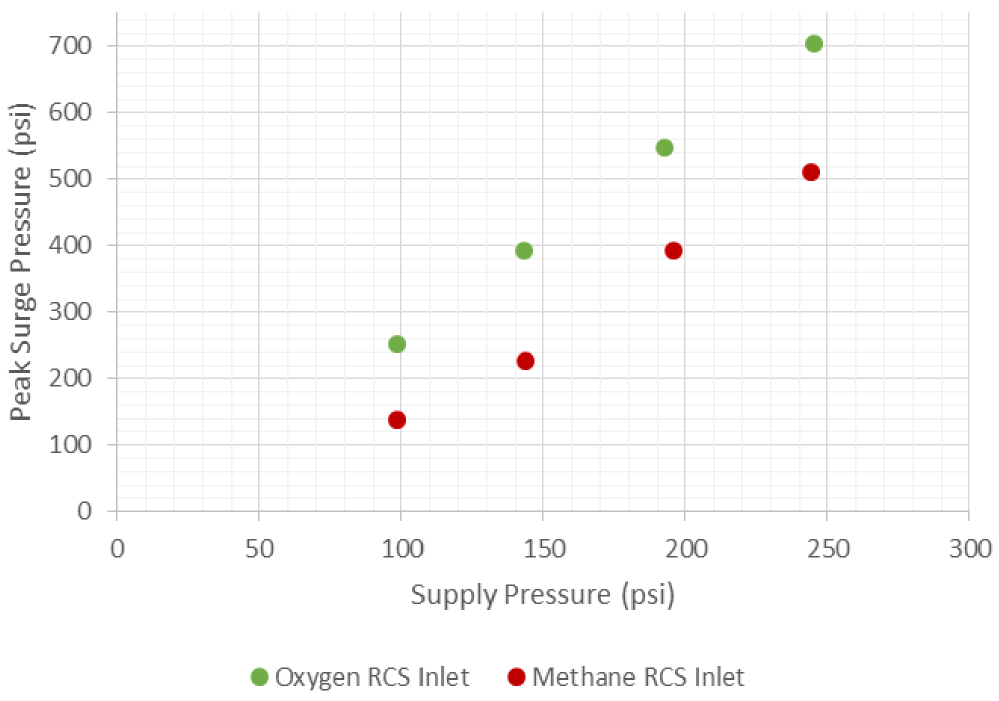
- After the initial trough from valve opening, a large amplitude follow-on pressure peak typically resulted
- The high magnitude valve opening transient is theorized to be the result of cavity formation/collapse
  - During ambient-thermal testing, this is due to a small pocket of gaseous propellant near the thruster valve inlet that collapses upon valve opening
  - During cold soak testing, this is due to the initial onrush of propellant into the thruster manifold at a much higher rate than under steady engine operation
- Additional effects of cavity collapse were observed during operation when pressure troughs from the opposite pod dropped below the local vapor pressure
  - The follow-on peak in these instances was more severe and contained a secondary peak that is thought to be due to cavity collapse (column separation)
- The high magnitude opening transients resulted in mixture ratio variation during the ignition startup since LO_2 and LCH_4 manifolds had different natural frequencies



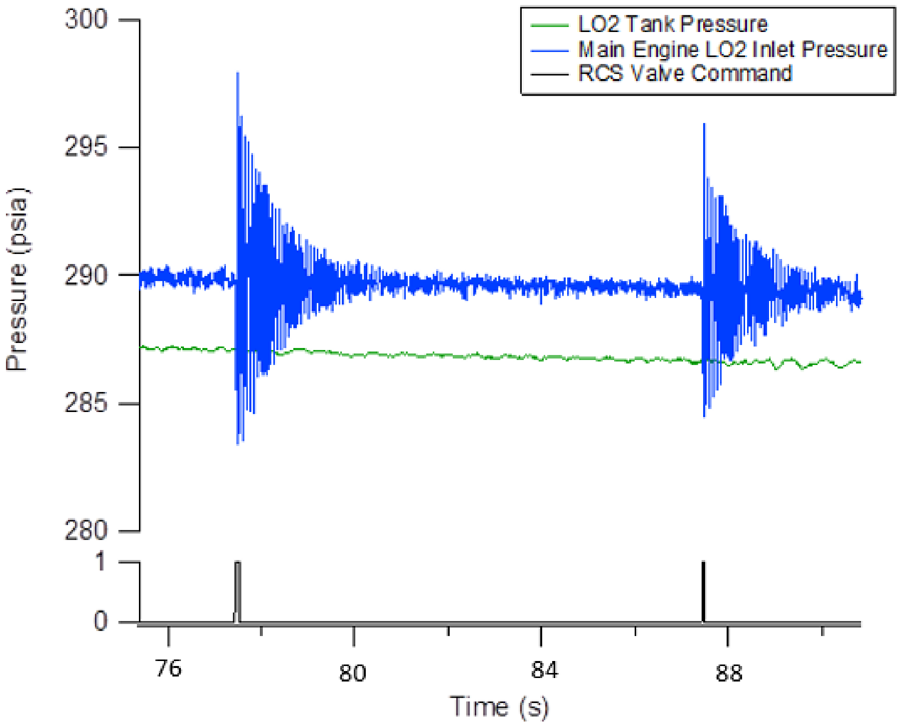
Oxygen manifold pressure trace for engine firing from nearby and opposite RCEs

Fluid Transients: Priming and Simultaneous Operation

- A series of priming tests were performed in which the manifolds were filled with GN2 pad gas at 1 atm and the propellant isolation valves were opened with variable upstream pressure
  - Peak surge pressures varied from 2.6-2.9 times supply pressure for O_2 and 1.4-2.1 times supply pressure for CH_4
  - No cold soak runs were performed, and all ambient-thermal tests were characterized by gaseous propellant damping
- During simultaneous main engine/RCS operation, transients from RCE operation had little impact on main engine inlet pressures
  - During cold soak testing (no ME), peak variation was still less than 10 psid; during ambient testing, less than 5 psid



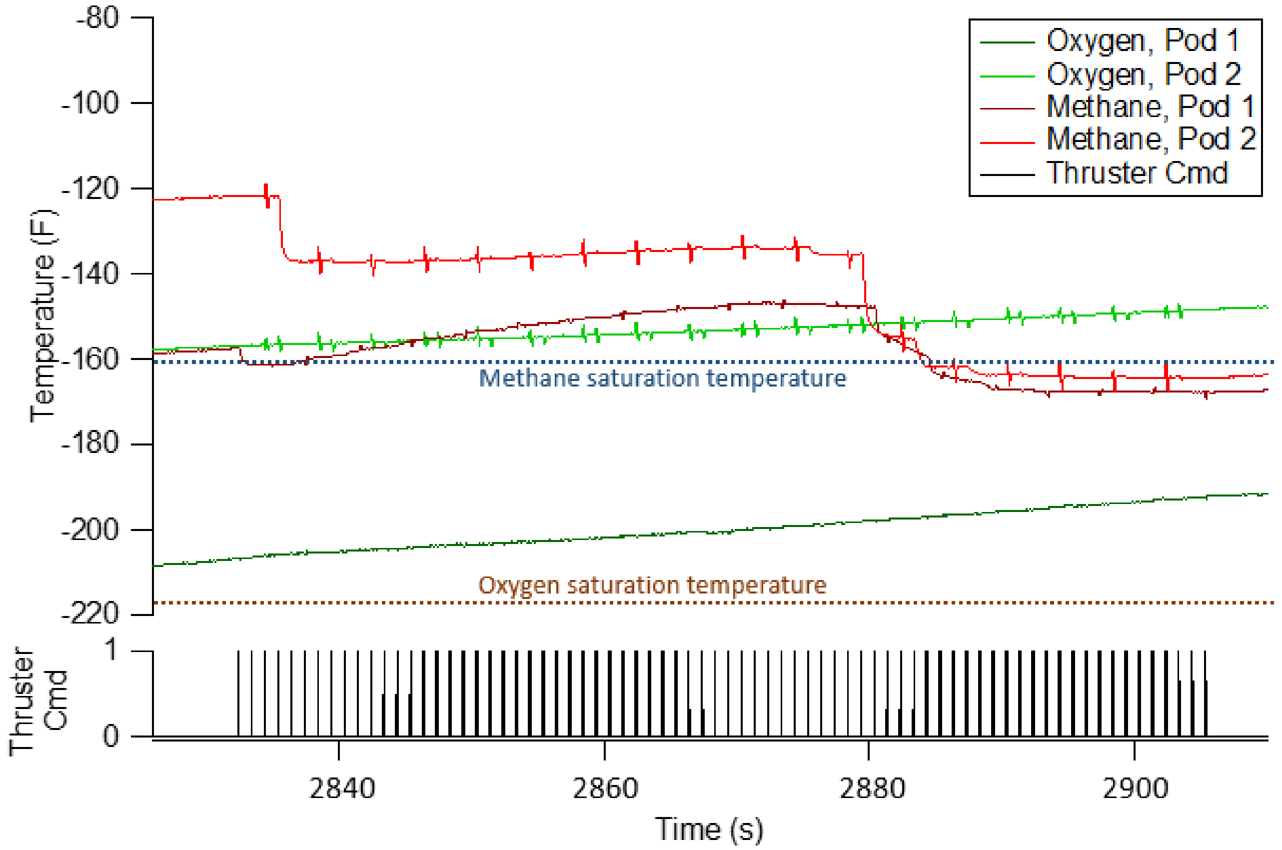
Peak surge pressure for various priming supply pressures



Engine inlet pressure variation during cold soak RCE operation (no ME operation)

Thermal Transients: Self-conditioning

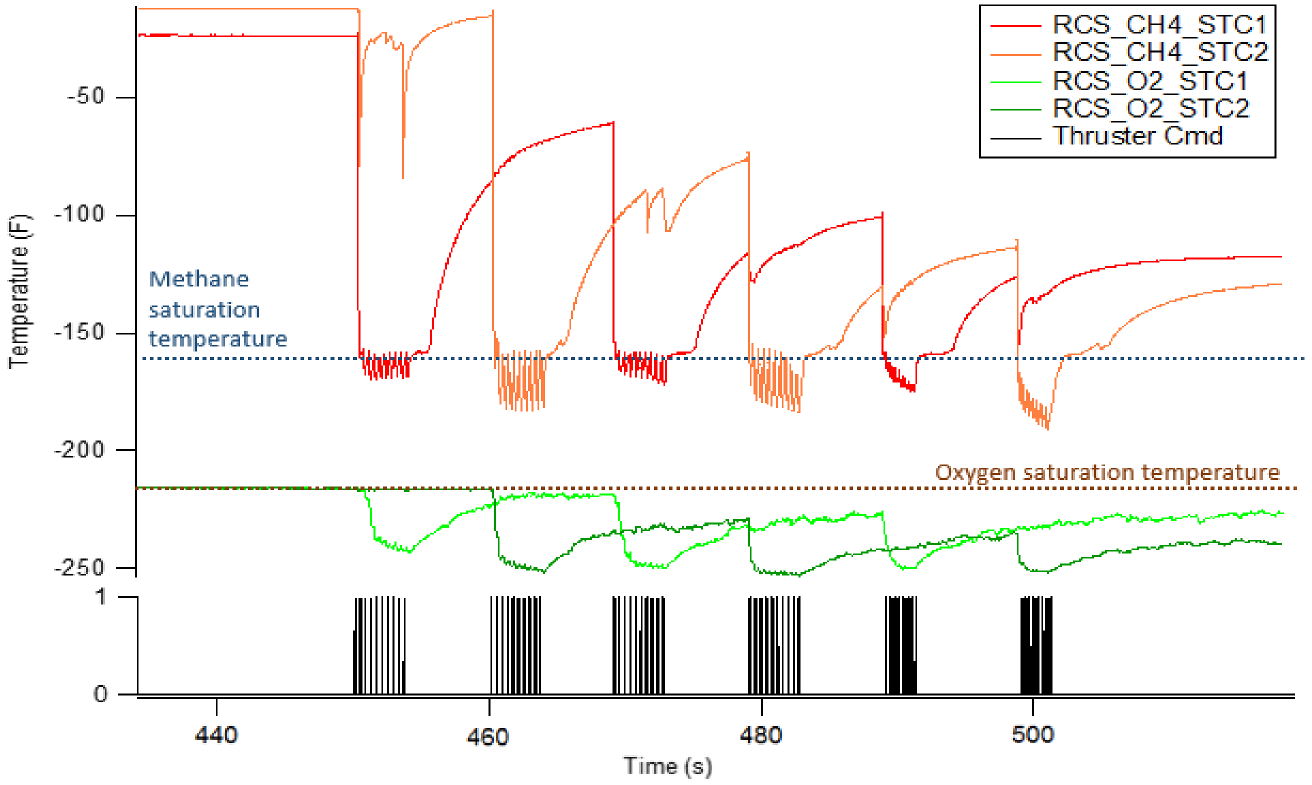
- A thermodynamic vent system (TVS) is one method to manage propellant conditioning for an RCS, but it results in propellant expenditure that could otherwise be used for attitude control
- Self-conditioning is a potentially advantageous alternative (or supplement), in which propellants are chilled-in through normal engine operation rather than controlled to a narrow band
  - Requires a wider engine operating box
  - Creates a variable MIB for GN&C
  - TVS can still be used for when necessary to maintain temperatures within operational limits
- Gas-gas operation in higher heat leak environments where low control authority is required (lower MIB, which can be good for station keeping)
- Higher duty cycle pulsing will result in manifolds chilling-in to liquid conditions (see methane temperature trace on right)



Manifold skin temperature near the thruster inlet for pulsing sequence in which methane manifold reaches liquid condition

Thermal Transients: Self-conditioning

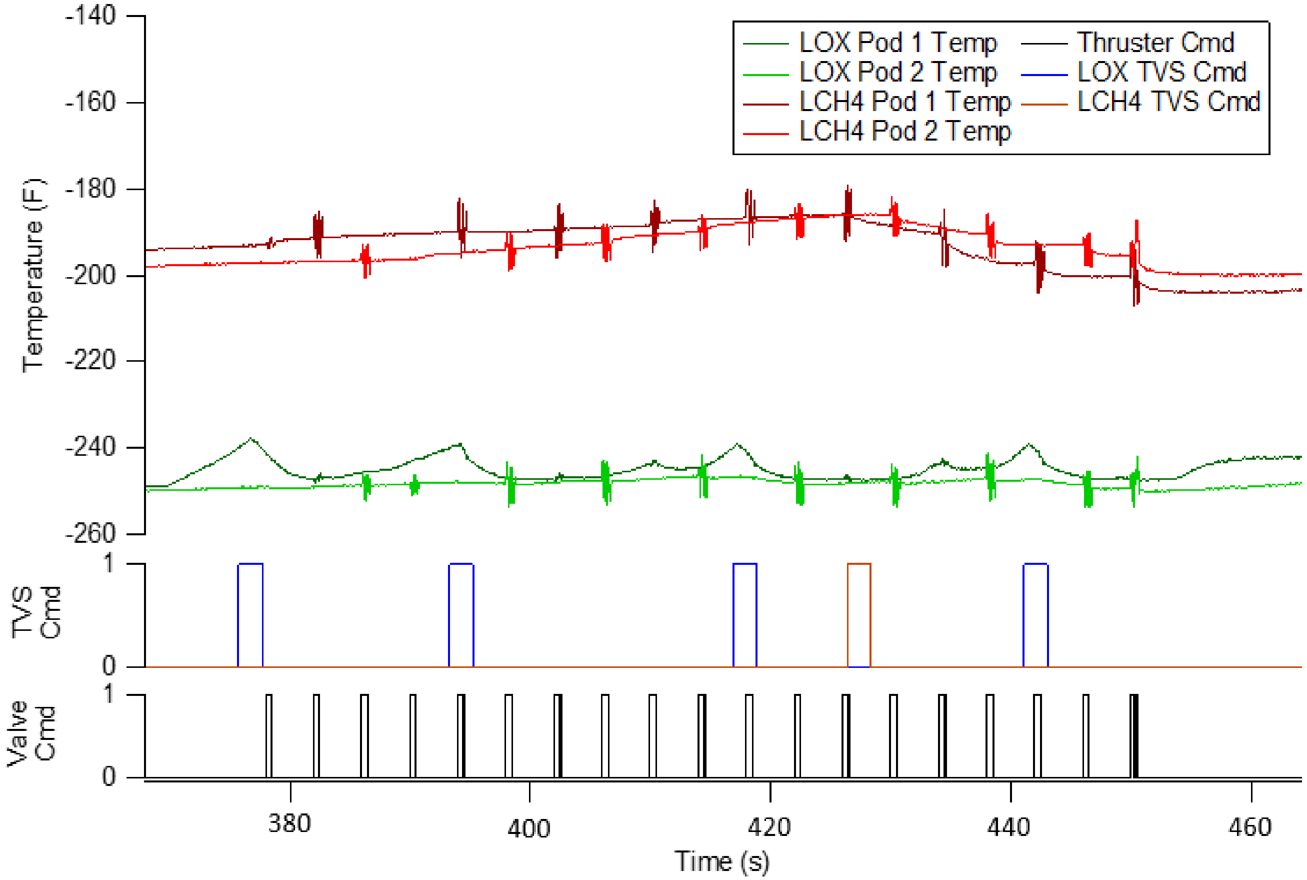
- Methane manifold typically chilled-in to liquid conditions faster than oxygen manifold, which allowed for benign transitions from gaseous RCE inlet conditions to liquid conditions
  - Never reached a condition in which the difference in chill-in time led to unfavorable mixture ratios for ignition
- Submerged thermocouple data indicated that for higher duty cycle pulsing, liquid conditions could be maintained at the engine inlets even in the high heat leak environment
  - These duty cycles can be challenging for the engines, however
- During cold soak testing, conditioning was not required and liquid conditions were maintained without RCE or TVS operation
- A self-conditioning scheme's feasibility is highly dependent upon the heat leak environment
  - A TVS would likely be required to supplement in most cases



Submerged thermocouple data for high duty cycle test where liquid conditions are reached

Thermal Transients: TVS Operation

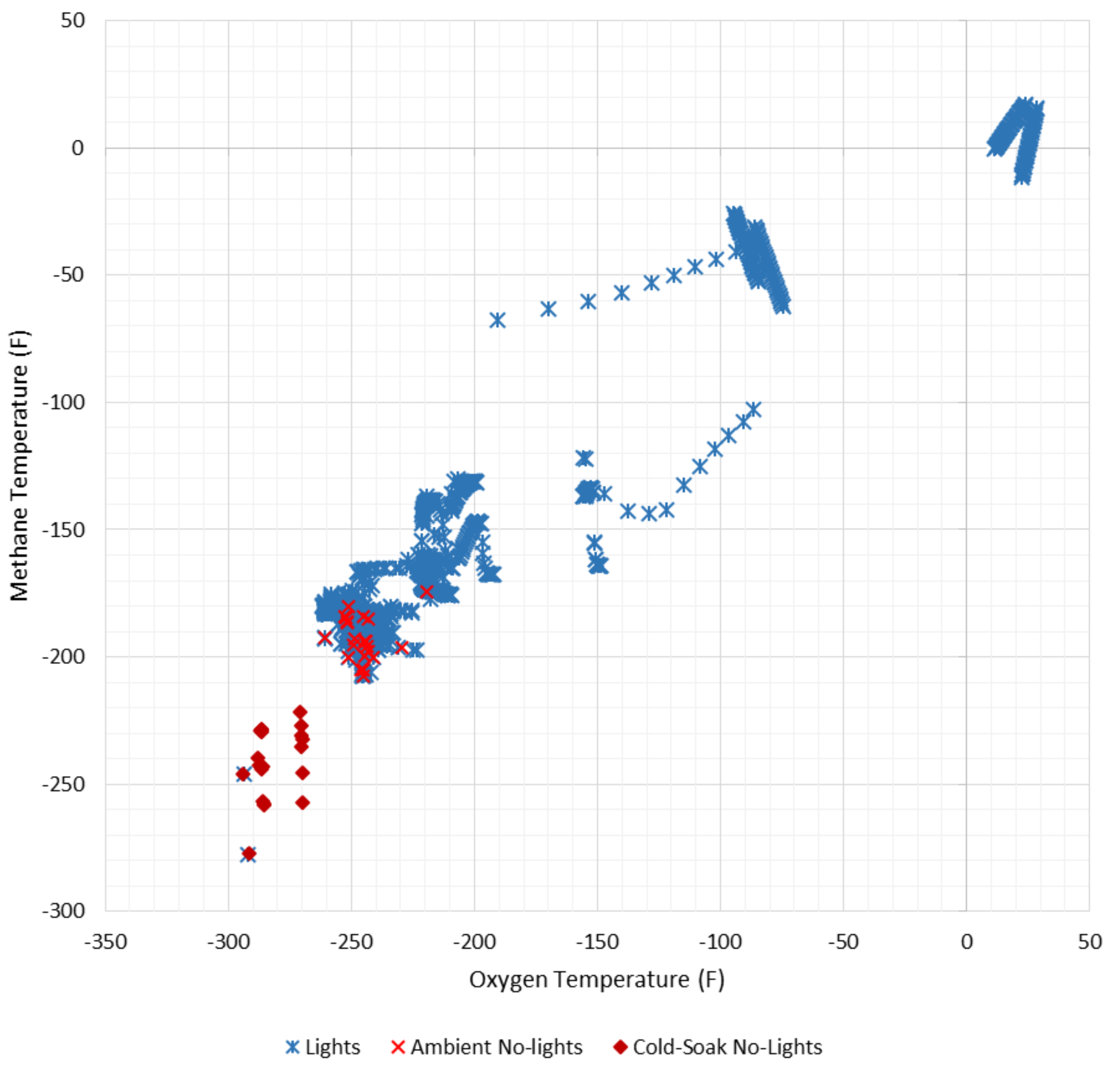
- TVS was used to condition the engines to a more specific operating point for many tests in the ambient thermal environment
  - Typical set point was either -250 °F/-190 °F (LO_2/LCH_4) or -218 °F/-160 °F
- Uneven heat leak between the two RCE pods resulted in different chill-in rates
  - In the test shown on the right, the oxygen TVS is operating every time the Pod 1 temperature rises to -240 °F, but on Pod 2, the temperature hardly rises between pulses
- Orifices were not sized to provide efficient propellant management, but rather, to allow for adequate cooling during ambient testing
  - Methane TVS operation resulted in a heat removal rate from the manifold of approximately 300 W
- Optimize performance based on projected maximum heat leak environment and expected duty cycle



TVS operation for liquid-liquid, 0.5-second paired pulses in which control band is in subcooled liquid range

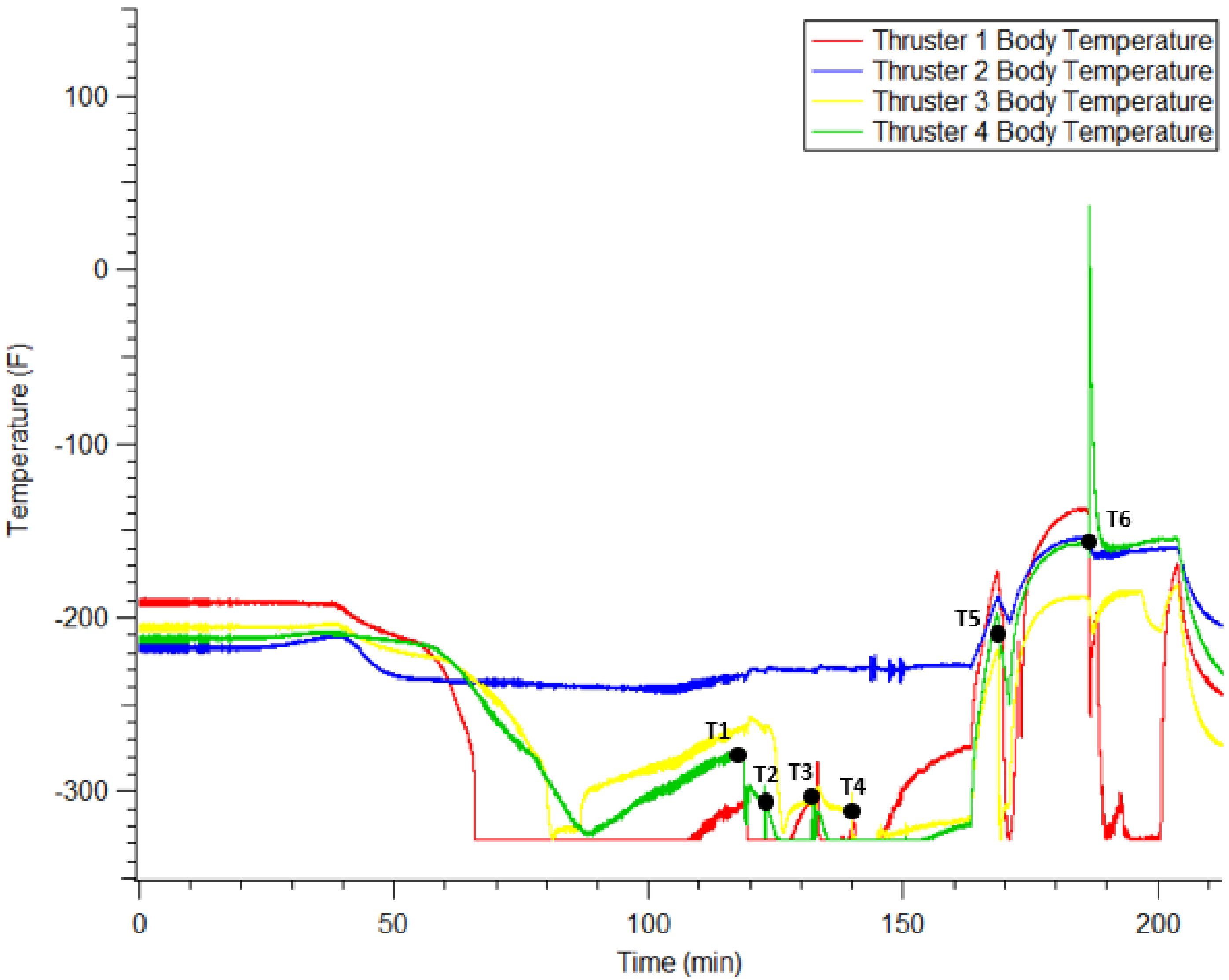
Ignition Mapping and Cold Soak Attempts

- 1,010 total ignition attempts across 40 tests
- 961 ignitions in 987 attempts during ambient-thermal testing
  - Inlet conditions ranging from gas-gas to saturated to liquid-liquid
  - Thruster body temperatures approximately -10 °F to 40 °F
  - LO_2 pressure 5-15 psi higher than LCH_4 pressure; typical set point was 310 psi/300 psi (LO_2/LCH_4)
  - Non-ignitions attributed to either poor propellant conditioning or pulse/spark length
- 2 ignitions in 23 attempts during cold-thermal testing
  - All attempts were 80-ms pulses (during ambient-thermal testing, 817 ignitions out of 832 attempts for pulses of this length)
  - Body temperatures started at -275 °F, and after successive no-lights, were warmed with GN2 purge to -218 °F (unsuccessful), and then -160 °F (successful)
  - Multiple test article and facility issues prevented further testing



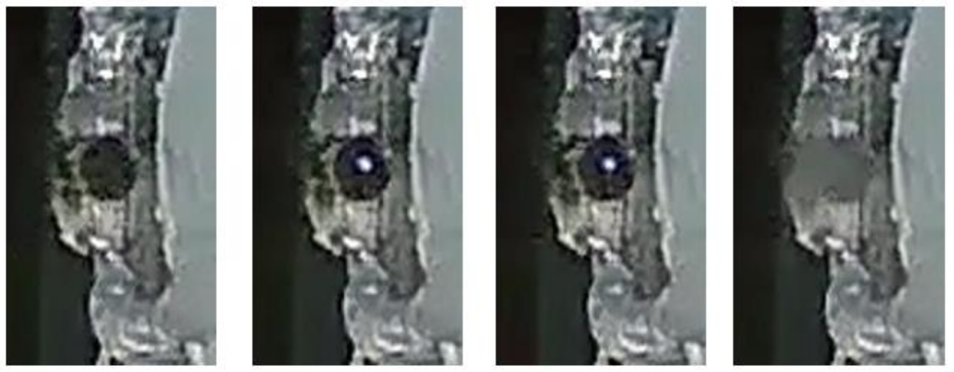
Body Temperatures During Cold Soak Tests

- Thruster body temperatures were measured by weld-on type K thermocouples
- LO_2 temperature near thruster inlets ranged from -270 °F to -290 °F, as measured by submerged type T thermocouples
- LCH_4 temperatures near thruster inlets ranged from -235 °F to -275 °F, as measured by submerged type T thermocouples

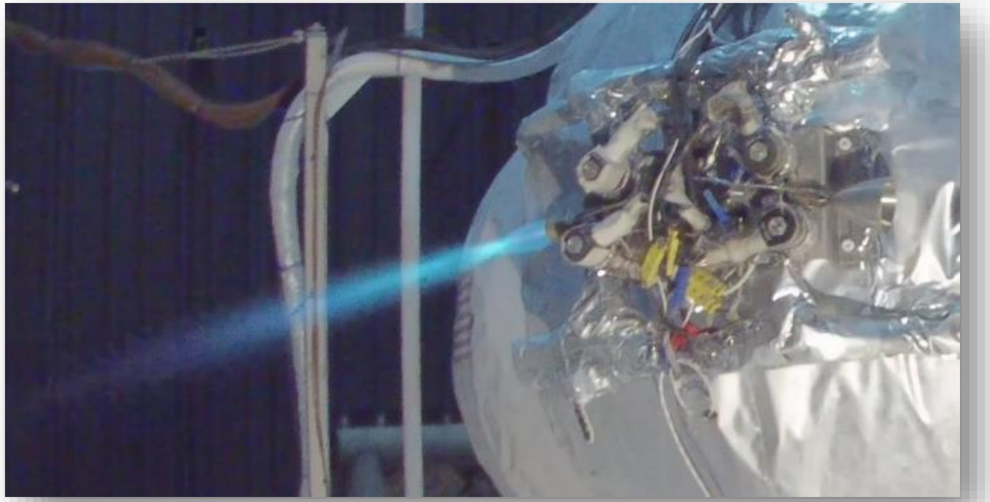


Non-Ignitions/Quenched Ignitions

- A camera was positioned looking up the throat of one RCE such that the ignition transient could be seen across 3-5 frames
  - In every unsuccessful ignition attempt on this engine, the core can be seen igniting briefly before it is extinguished and a cold flow results
  - Video is unavailable for the other RCEs, but the same phenomenon is likely to have occurred
- Contributing factors to quenched ignitions:
  - Low cold flow pressure due to reduced vapor pressure at colder propellant temperatures and less heat transfer from thruster bodies
  - Colder/denser fuel film cooling potentially reduces MR below the flammability limit during the transient; also serves to pull energy away from the higher MR core
  - Relatively low ignition energy (22-24 mJ) could result in quenched spark kernel at the lower wall temperatures; extending the spark past valve closure also might have improved ignitability
- It is theorized that the valve opening transient could also potentially play a role by creating wide MR swings into regions unfavorable for ignition



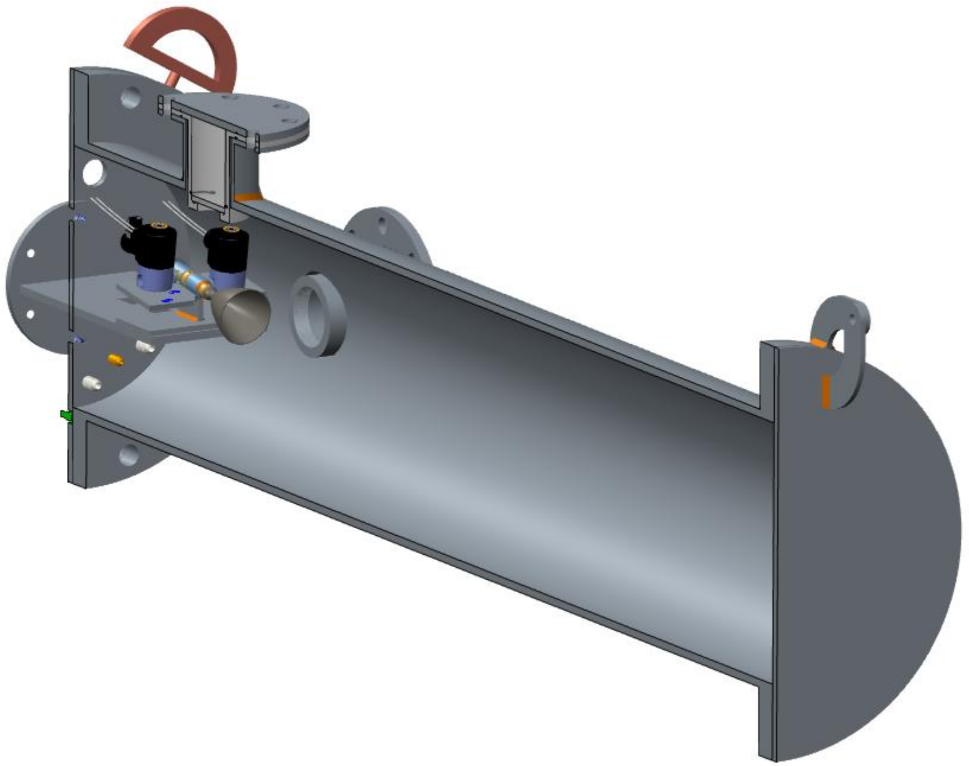
Frame-by-frame imagery of quenched core ignition



Thermal-vacuum ignition of 7 lbf RCE, achieved after GN2 purge

Forward Work

- Additional environmental testing will be performed on the RCEs to better understand the lower temperature ignition limits
  - Planned FY18 testing at JSC in vacuum pipe with LN2 thermal conditioning system
  - Will include a better sweep of operating conditions at a range of low body temperatures to determine low temperature ignition boundary
- Additional testing of thruster modifications for improved low temperature ignitability
  - Higher temperature materials to allow for increased overall MR
  - Improved coil-on-plug design
  - Improved film cooling design
- Vehicle level thermal model under development using SINDA/FLUINT
  - Will include model of RCS manifold and TVS to predict required TVS consumption or engine duty cycle to maintain desired conditions for a given heat leak environment
- Water hammer model development using test data as anchor, with focus on predicting large magnitude opening transients
  - EASY5 used for initial assessment but cannot model cavitation
  - SINDA/FLUINT will be used to model cavitation in simplified geometry



Follow-on testing of RCE to occur in vacuum pipe with thermal conditioning system

Conclusions

- This testing represents the first known integrated cryogenic RCS demonstration in a thermal vacuum environment
- Data was obtained under simulated altitude and thermal vacuum conditions from 40+ RCS specific sensors:
  - Manifold priming
  - Fluid transients due to RCE operation
  - Thermal conditioning of manifolds through RCE operation only
  - TVS operation
  - Main engine/RCS interaction
  - Ignition across a wide range of propellant conditions
- Ignition issues were discovered during cold soak testing with cold thruster hardware
  - Successful ignition was finally obtained after warming thruster bodies with GN2 purge
  - Improvements are expected by increasing overall engine MR
  - This result highlights the importance of environmental testing in future RCE development
- Other key findings include:
  - Priming peak pressures 1.4-2.9 times supply pressure with 1 atm GN2 pad gas
  - Valve opening transients were more severe than valve closing transients, with some pressure peak amplitudes >600 psid
  - Higher transient pressures during cold soak testing
  - RCS feed system transients had minimal impact on main engine inlet conditions (less than 10 psid)
  - Self-conditioning is feasible for maintaining liquid or near-liquid conditions at RCE inlets, but requires high DC in ambient heat leak environment
  - Under cold soak conditions, no effort was required to maintain liquid at RCE inlets

Questions?

COP Ignition Architecture