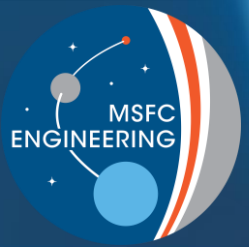
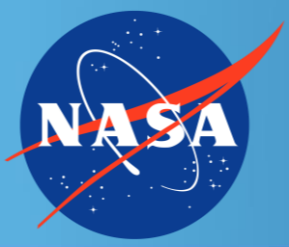


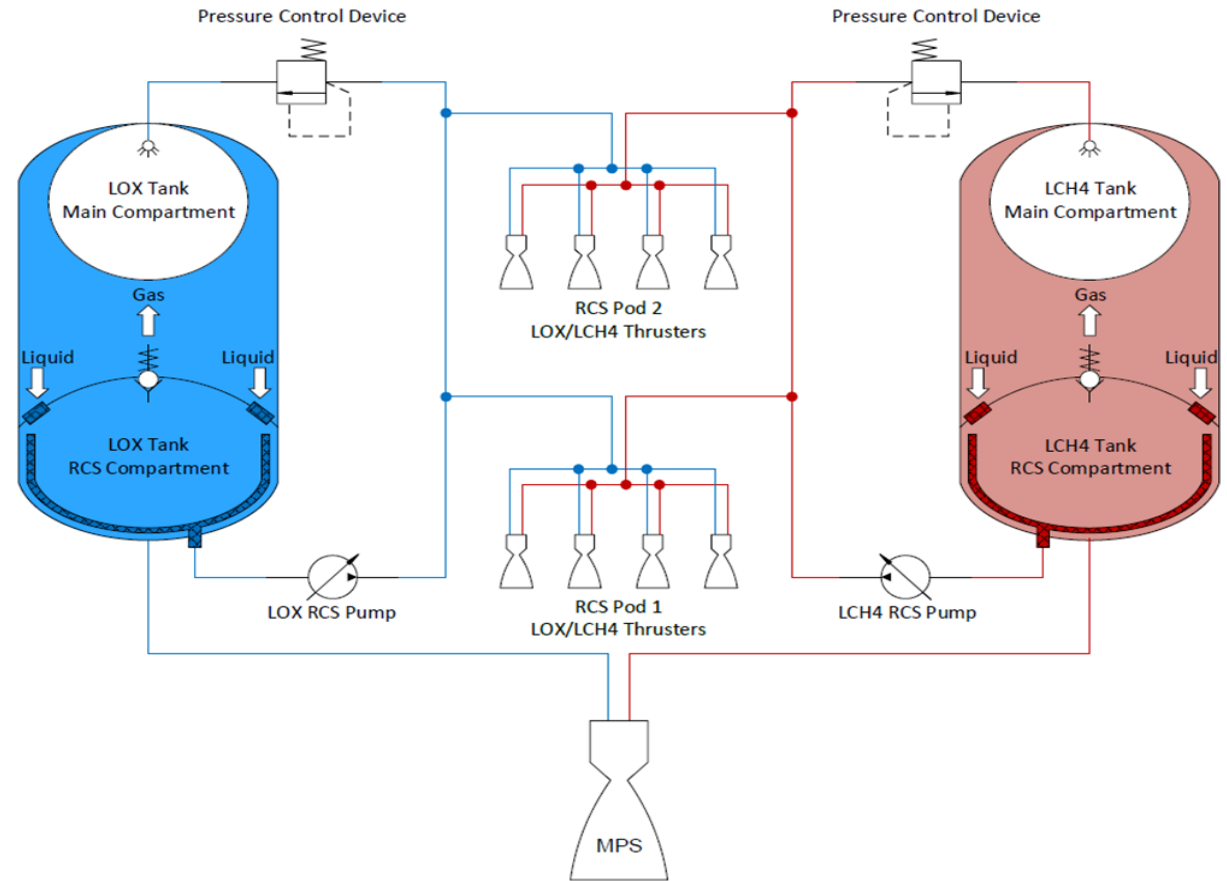
PROOF OF CONCEPT TESTING FOR INTEGRATED REACTION CONTROL SYSTEM

Cameron Hines – Marshall Spaceflight Center
Anson Koch - Marshall Spaceflight Center
Hannah Cherry - Marshall Spaceflight Center



BACKGROUND

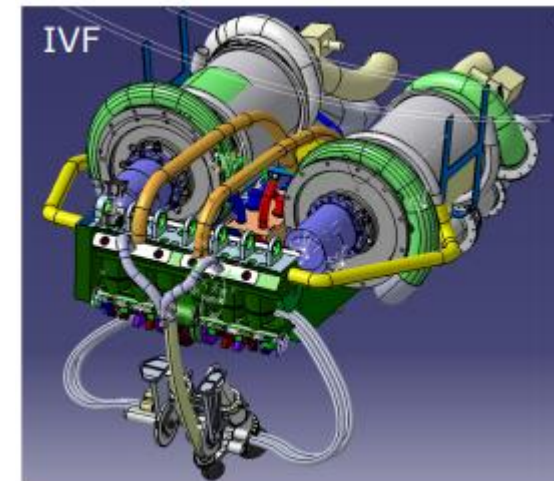
- An Integrated Reaction Control System (IRCS) uses common propellant between Main Propulsion System (MPS) and Reaction Control System (RCS)
- In this IRCS concept, Reaction Control System Thrusters are supplied propellant by an electric-pump-fed, pressure-controlled manifold



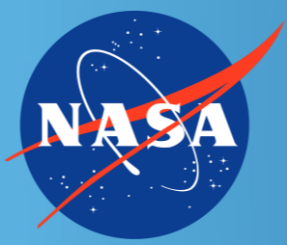
- IRCS concepts have been around for a short while
 - Morpheus (2011-2012)
 - Integrated Cryogenic Propulsion Test Article (2016-2017)
 - ULA Integrated Vehicle Fluids/Advanced Cryogenic Evolved Stage (2016-)
- New interest from NASA in context of larger exploration vehicles
 - Human Landing System
 - Nuclear Thermal Propulsion
 - Mars Chemical Propulsion Stage(s)
- Multiple unique concepts
 - Pressure-fed MPS/RCS with common tanks
 - Harvesting boiloff and/or gasifying liquid
 - Pump-fed pressure manifold



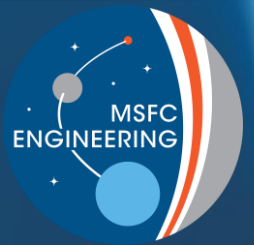
[1]



[2]



Benefits of IRCS



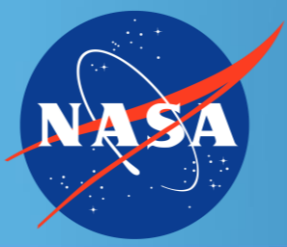
- Usual motivation – Mass reduction
 - Remove dedicated RCS propellant and pressurant tanks
 - Use higher-ISP propellants for RCS
 - Estimates range from ~10%-30% propulsion system mass reduction
- Enable common fluid system
 - Reducing number of fluids enables refueling and re-use of systems
 - Significant interest in Cryogenic Fluid Management technologies
 - Cryocoolers/zero-boil off, autogenous repress, propellant transfer, etc.
 - IRCS eliminates one of the largest fluid systems and replaces it with cryogenic propellant
 - Overall changes to architectures enabled by common fluid system may outweigh the more tangible gains in performance for one particular vehicle

Liquid-Pump IRCS Motivations

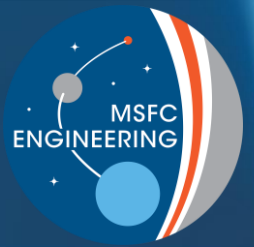
- Activity started as a Mars-propulsion architecture study
 - Liquid-pump design intended to power 350-lbf liquid-liquid RCS thrusters
 - Current design is for 100-lbf liquid-liquid RCS thrusters
- Pump-fed design intended to solve two perceived challenges from ICPTA
 - Gas at thruster inlet during startup
 - Pressure-fed propellant tanks



[3]

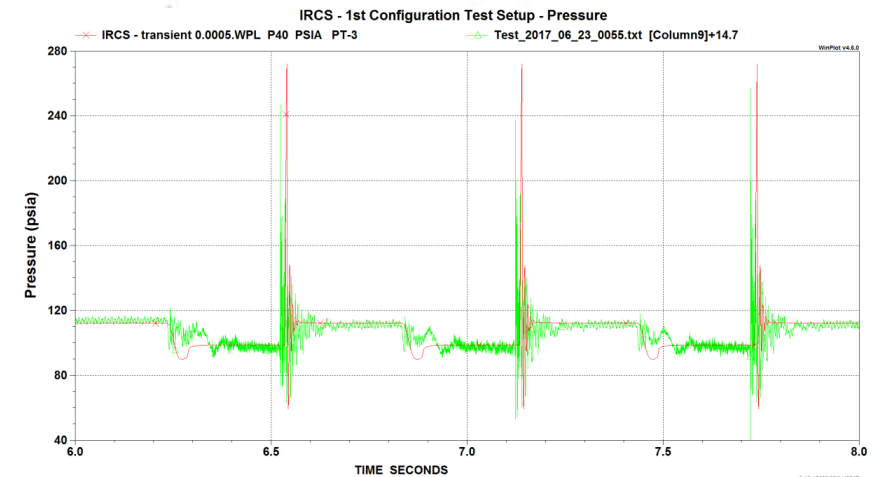
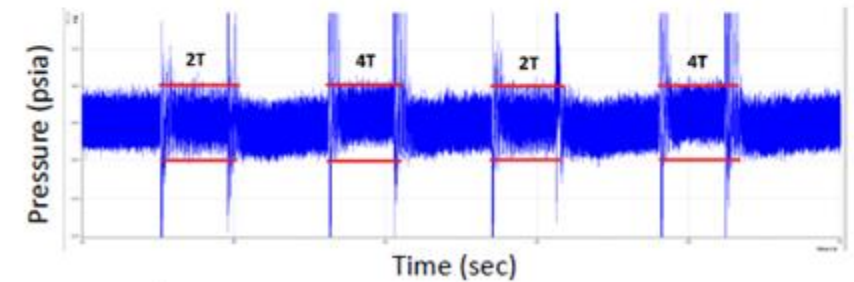
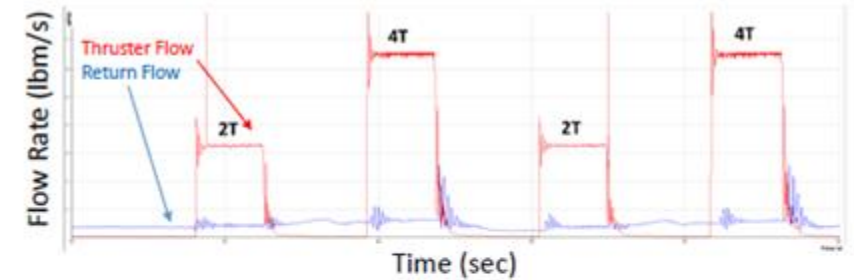


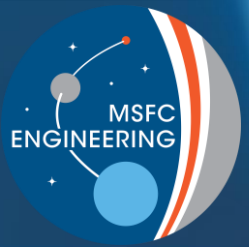
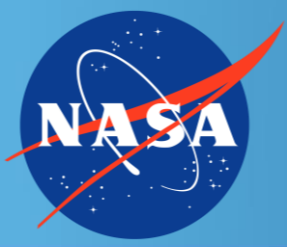
Liquid-Pump IRCS Technical Challenges



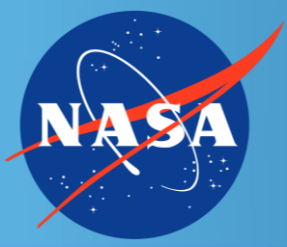
- Keeping the manifold chilled during non-operation
 - Main engines have a chill-down prior to firing and only a few firings at known intervals
 - reaction control thrusters fire much more frequently with intervals driven by control bands
 - Current solution uses an “idle mode” that recirculates fluid at a lower flow rate through the manifold
- Managing heat load to tank from recirculation
 - Pump adds energy to the fluid that then returns to the tank – effectively a heat load
 - Possibility of two-phase flow occurring downstream of pressure-control device if fluid is sufficiently cold
 - Adding another line to the tank adds another structural heat penetration
- Managing transients
 - Water hammer is a common technical challenge on reaction control systems
 - Liquid-pump IRCS adds an additional challenge from the coupled dynamics of the pump and pressure control device
 - This requires a pressure control device that can respond rapidly to large fluctuations in pressure, and a pump that can rapidly change its operating point

- Previous water-flow testing looked at pressure transients
- Models match test data reasonably well
- Testing also investigated dynamically throttling the pump to minimize return flow between thruster pulses
 - Pulses on order of 1 second

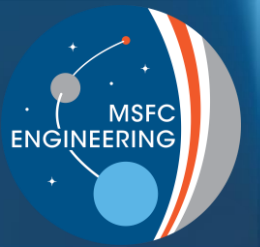




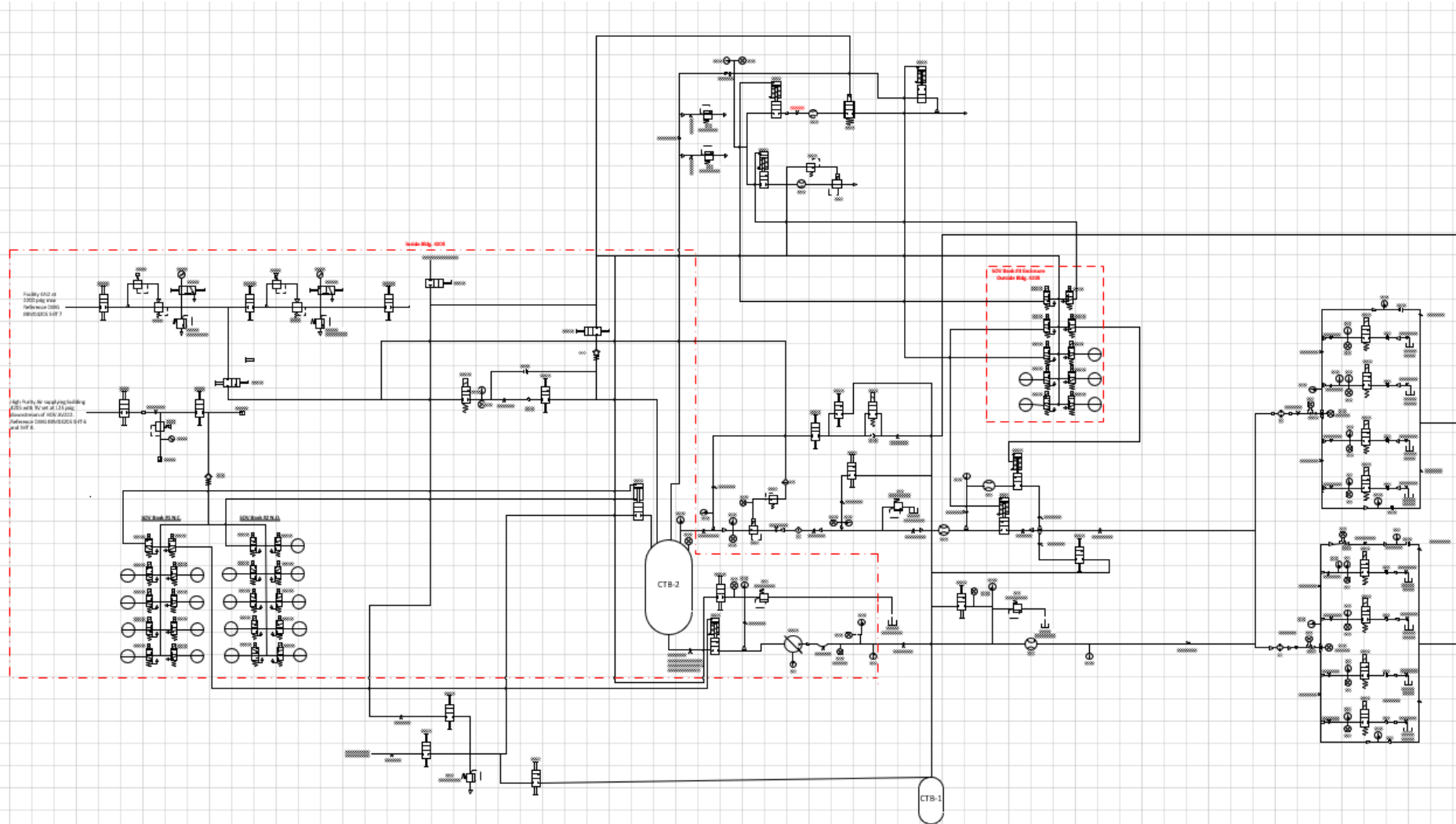
CURRENT GROUND TEST WORK

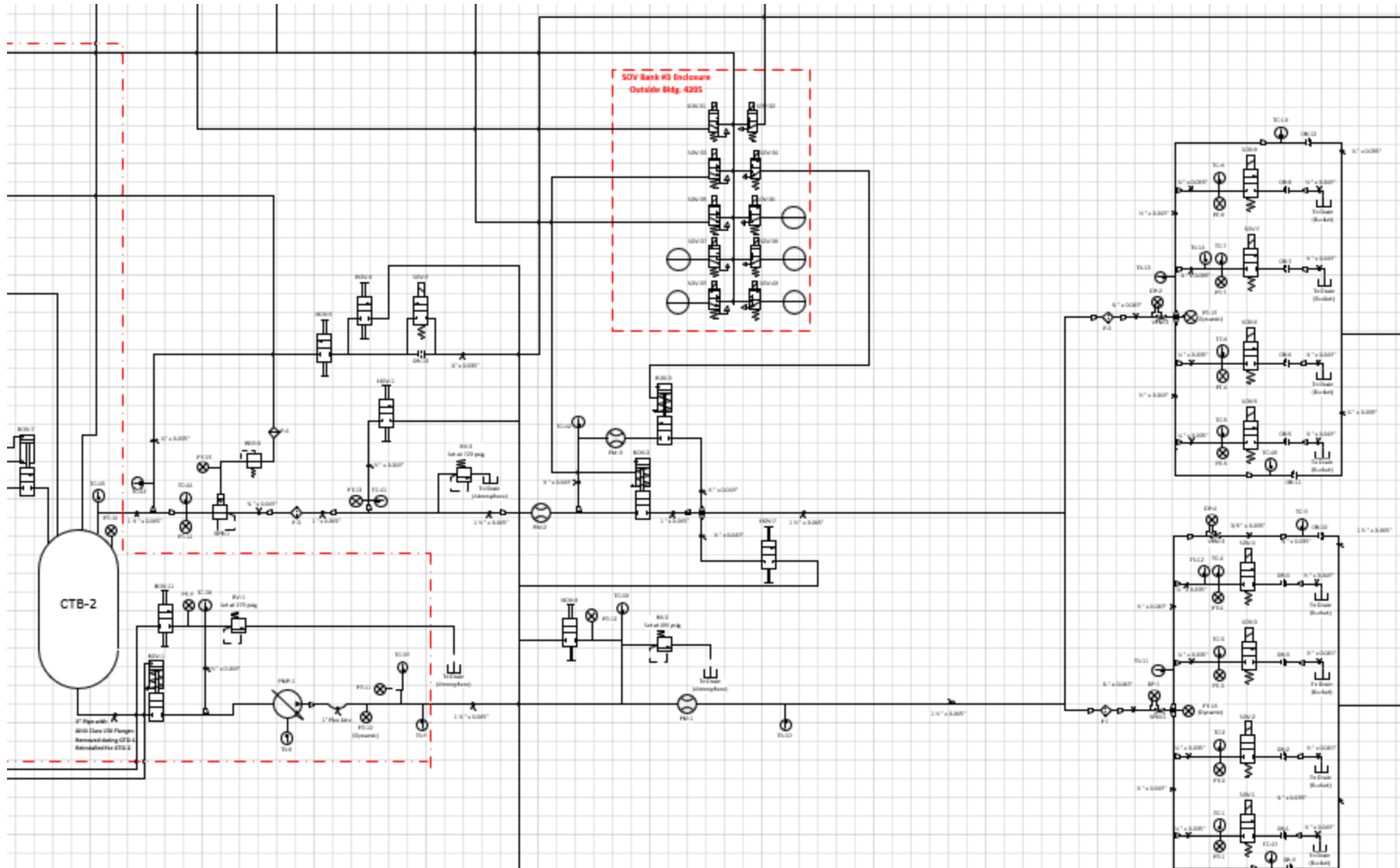


Test Objectives



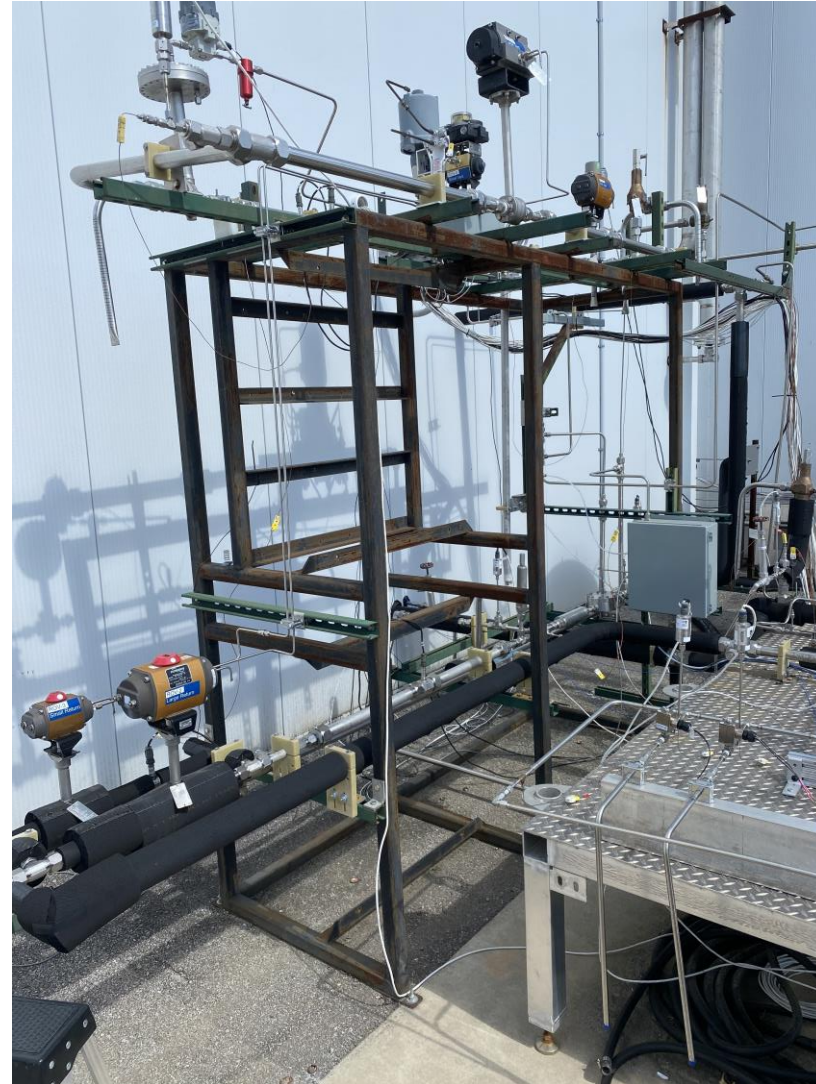
- GTO-1 – Measure ambient heat load on storage tank
- GTO-2 – Determine IRCS Performance in all operating modes
 - GTO-2.1 - Determine IRCS Performance in Idle Mode
 - GTO-2.2 - Determine IRCS Performance in Active Mode with constant flowrate
 - GTO-2.3 - Determine IRCS Performance in Active Mode with pulsing flowrate
- Measurements of Interest
 - Tank pressures and temperatures
 - Pressure and quality at “thruster” inlet
 - Enthalpy at recirculation inlet and outlet
 - Flowrates
 - Skin temperatures along recirculation line
 - Pressure and quality downstream of pressure control device (back pressure regulator (BPR))

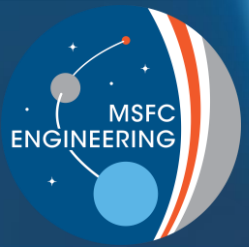
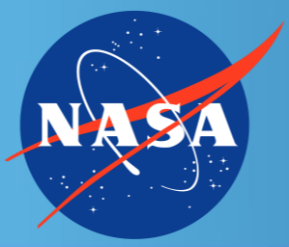




- LN2 used as simulant for LOX
- Thrusters are simulated as solenoid-valve and orifice
 - Mass flowrate is .225 lbm/s per thruster, equivalent to LOX flowrate for 100 lbf thruster at 2.6-3.5 mixture ratio
- Chill lines flow around each thruster “pod” to provide chill-in during “idle” mode
- Industrial COTS pump and BPR are used for the manifold
- Cryogenic Testbed 2 Tank is used as test tank

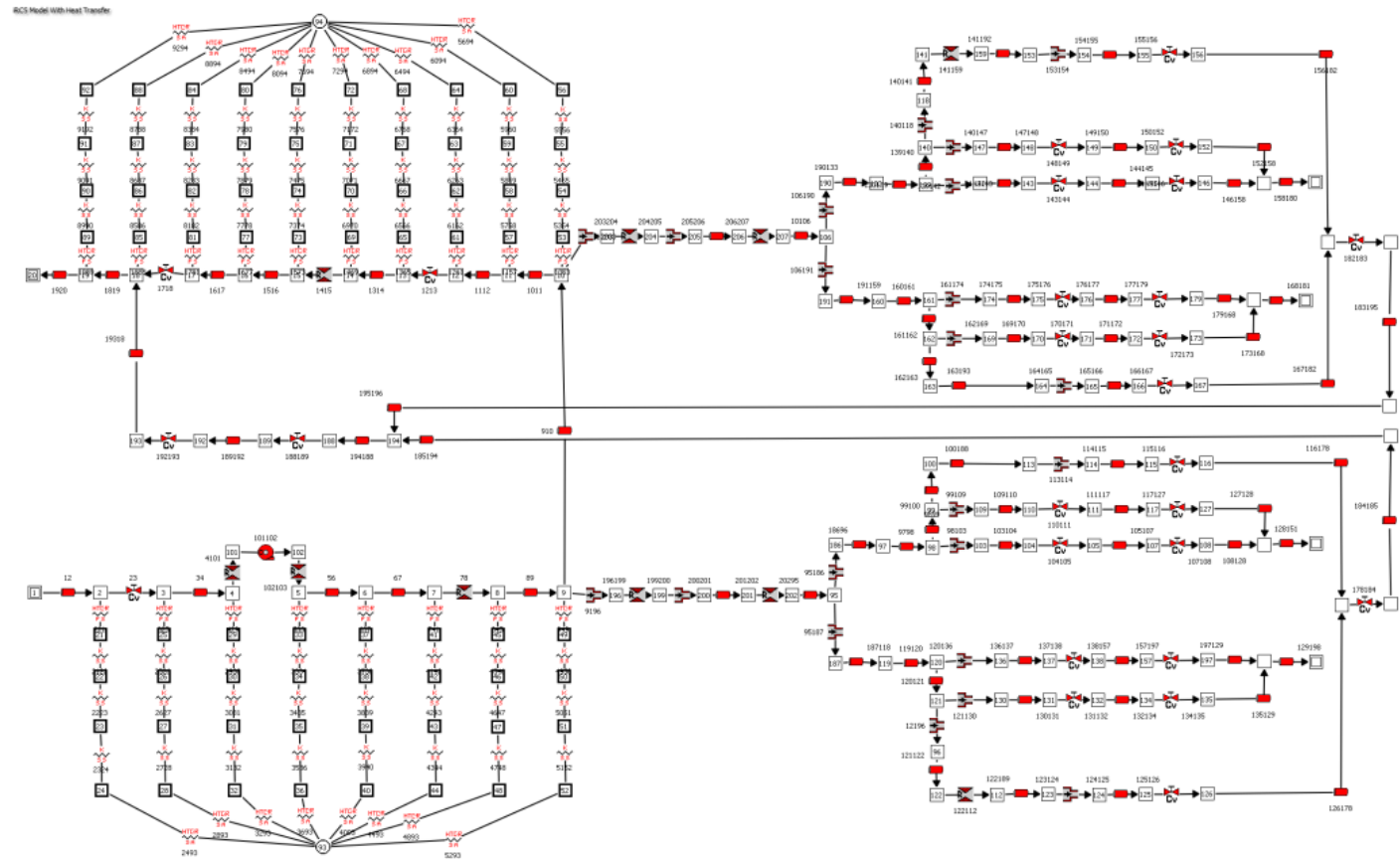


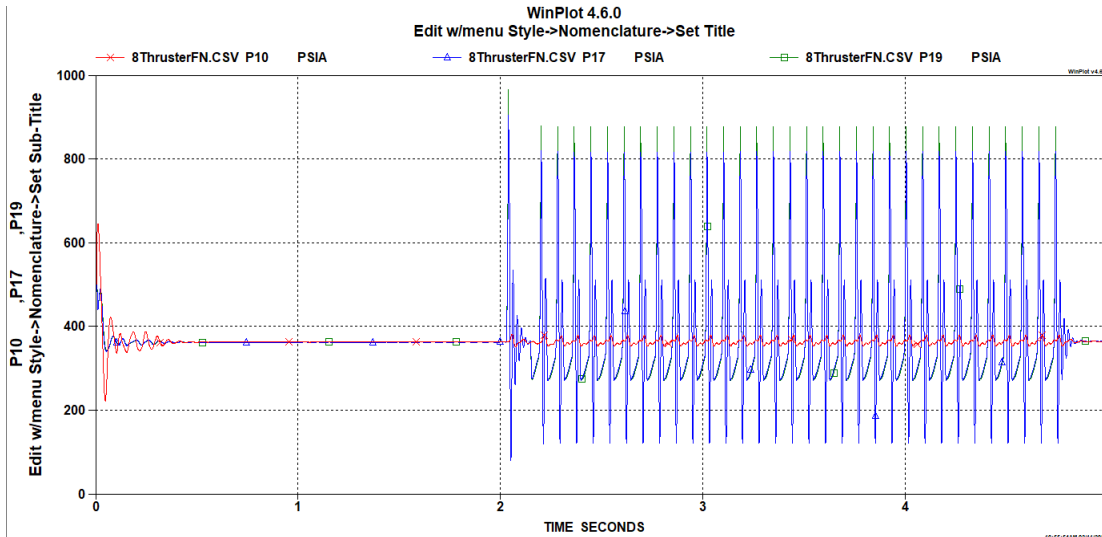




CURRENT ANALYSIS WORK

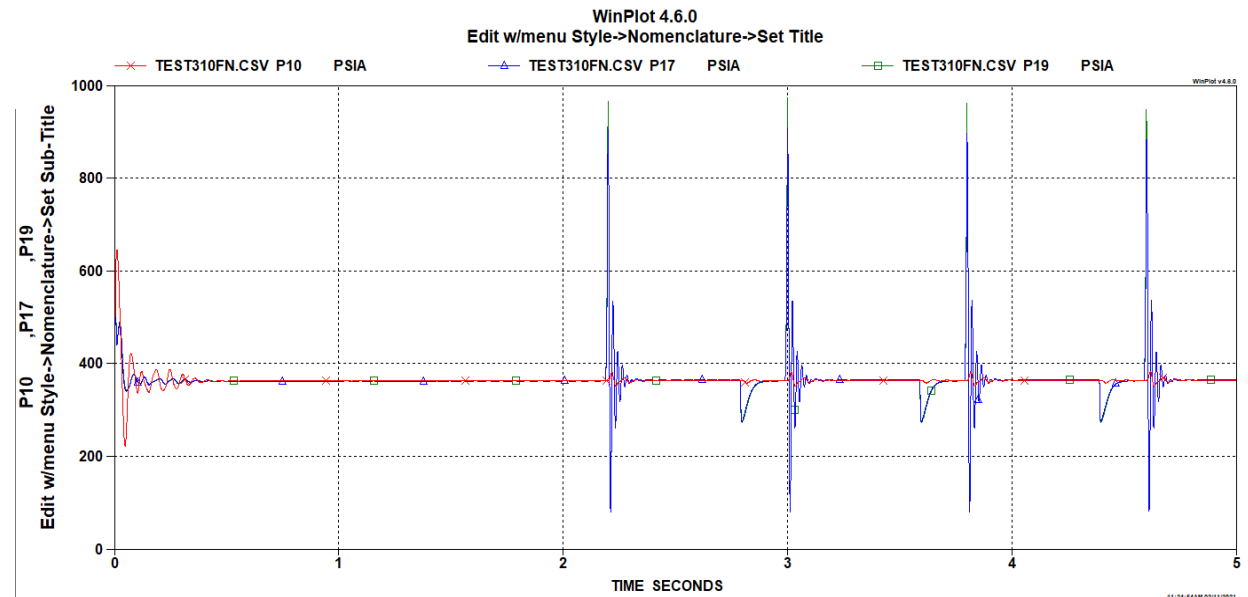
- IRCS developed two models using Generalized Fluid System Simulation Program
- Steady State Model models heat transfer in higher detail
- Transient model looks at water hammer with less detailed model (no heat transfer)
- Pre-test Predictions produced for select test cases

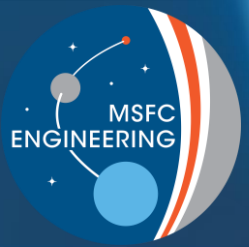
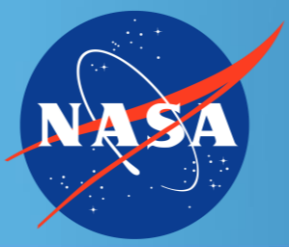




- Current estimates for heat load from recirculation are 5.5-20 kW
 - Driven largely by size of pump flowrate
 - Substantial reduction needed

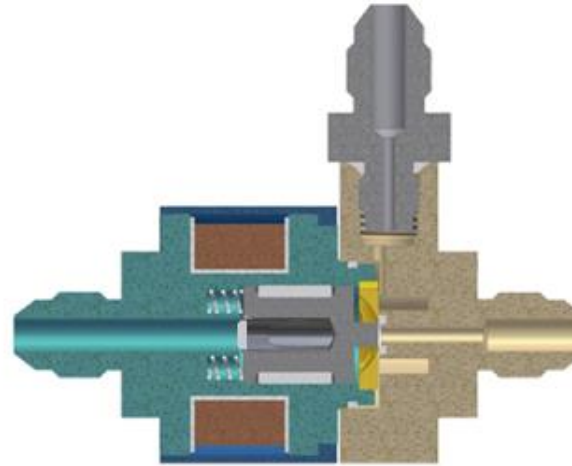
- Large pressure spikes and smaller slumps
- Pressure transient at thruster inlet, but much less in recirculation line





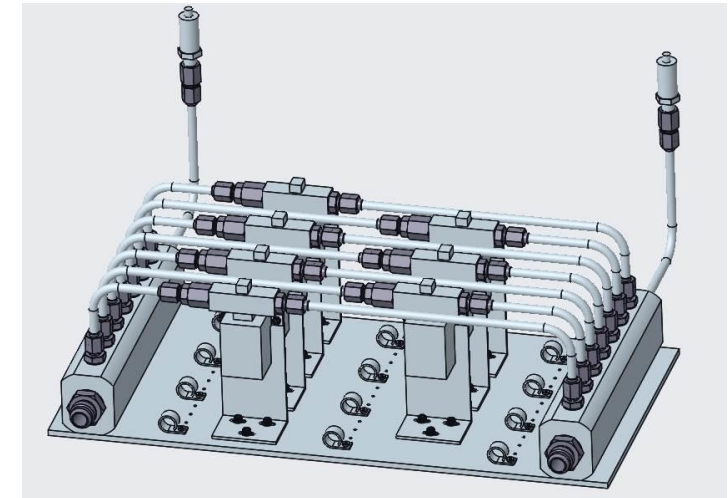
CURRENT COMPONENT DEVELOPMENT

- IRCS is partnered with component development projects for a second-generation IRCS testbed
- Three-Way Valve for thruster chill
- Small Electric Pumps
- Flight-like Back Pressure Regulator
- “Digital Valve” for pressure control



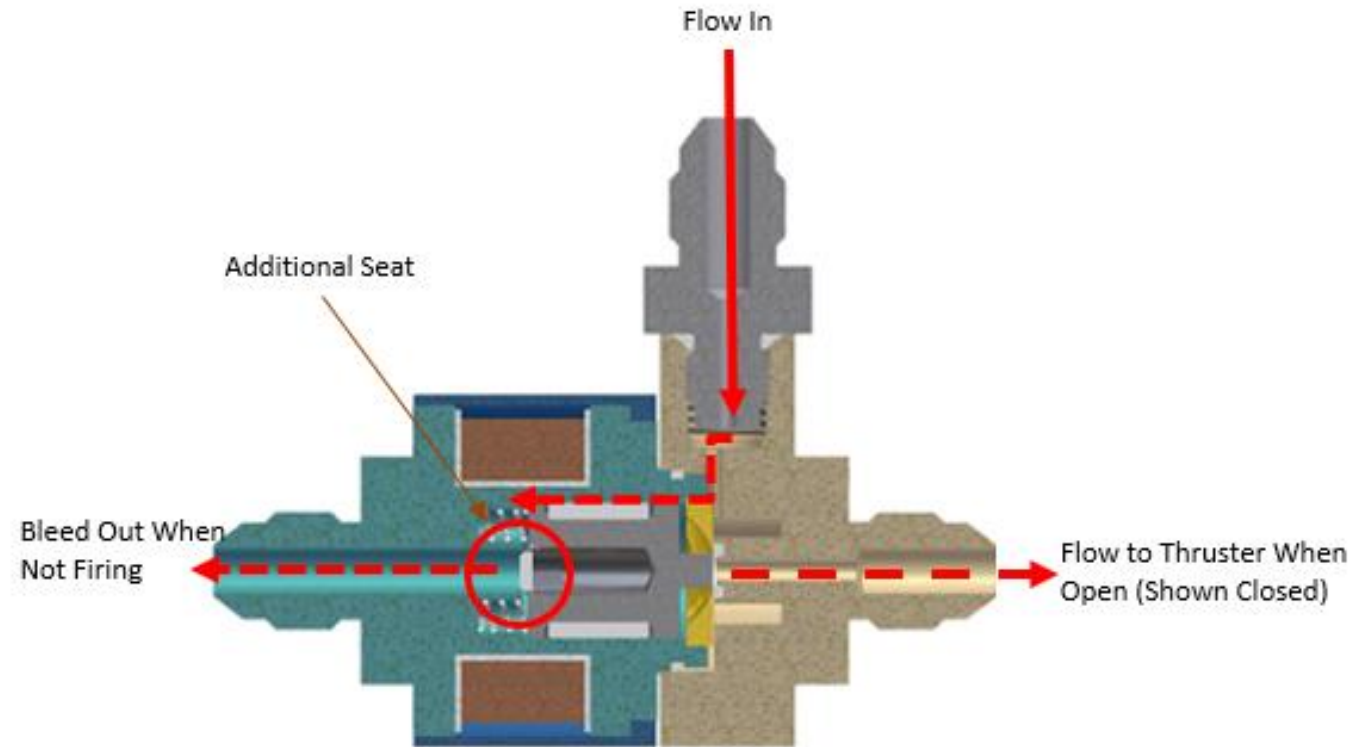
Three-Way Valve

Digital Valve



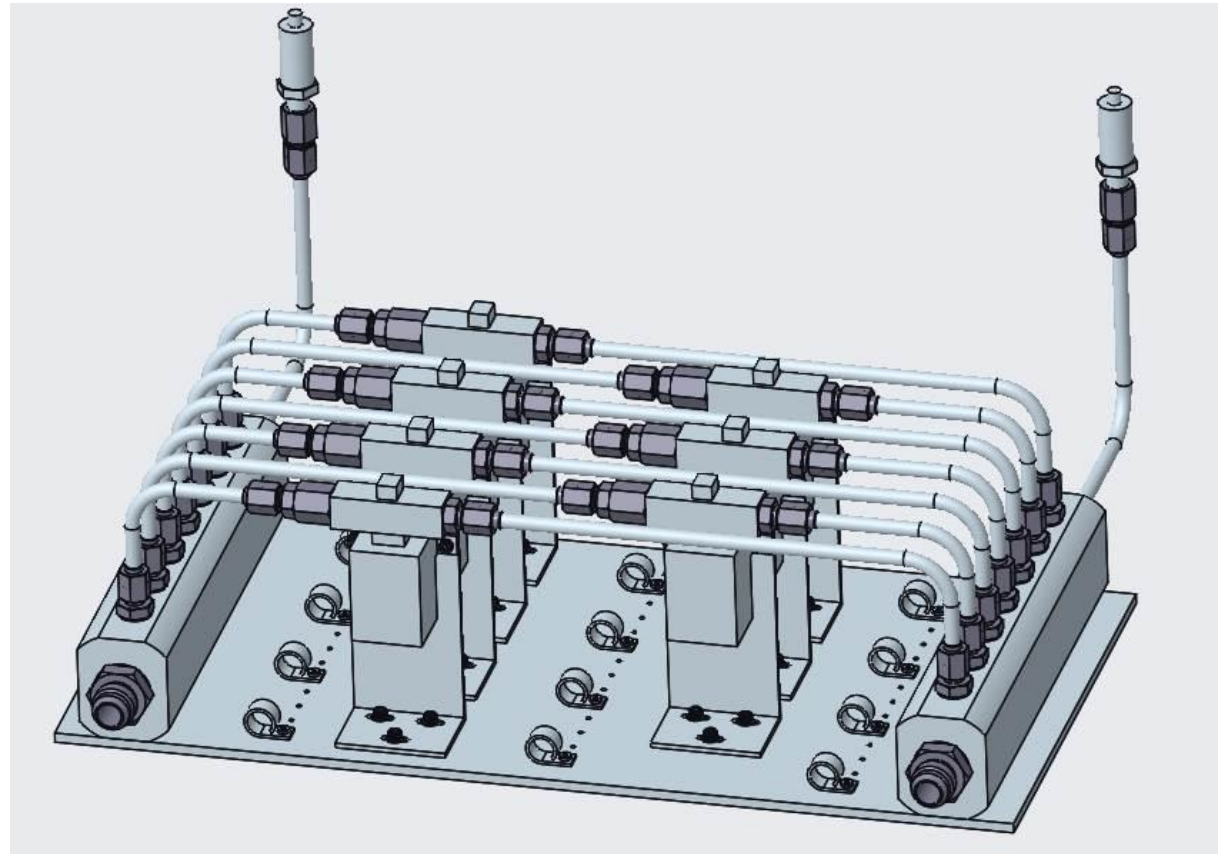
Three-Way Valve

- In development through ER14 at MSFC
- Modified version of valve with constant bleed out
- Adds a second seat – only bleeds when not firing
- Would enable removal of chill lines around thruster pod



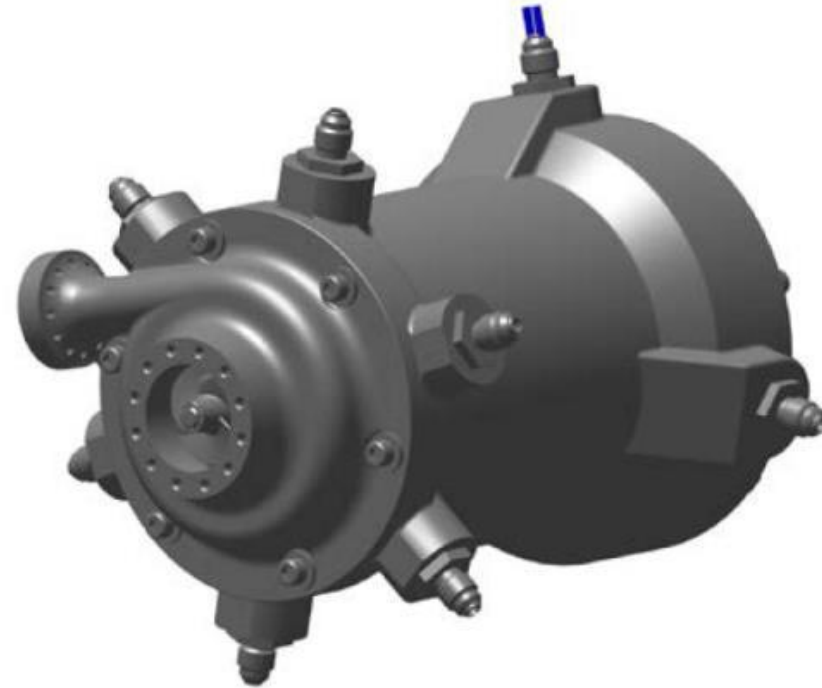
Digital Valve

- In development through ER14 at MSFC
- Uses 6 Solenoid Valves in parallel to achieve varying Cv
- Responds 5x faster than a variable position valve for 50% increase in power

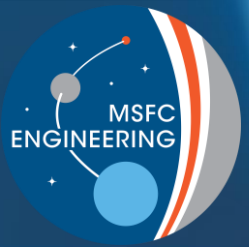
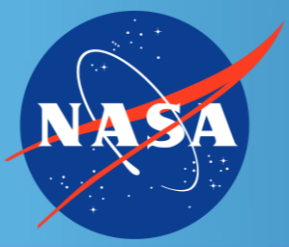


Electric Pump

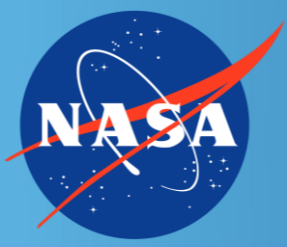
- IRCS has reached out to multiple vendors concerning development of a small electric pump
- Need pump with flowrate of .54-2.16 lbm/s and 325 psid head rise
- Candidates have included AMPed LOX impeller and commercial gear pumps



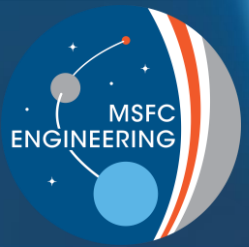
AMPed Electric Pump Model [4]



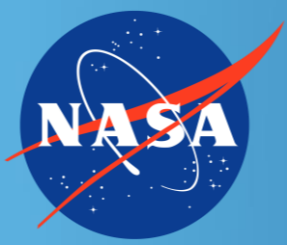
FUTURE WORK AND SUMAMRY



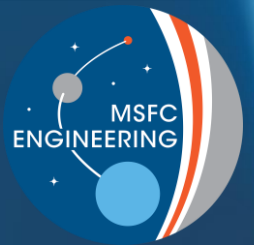
Future Work



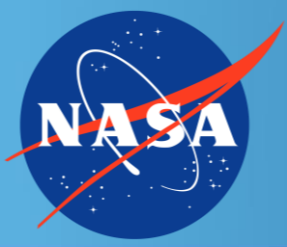
- Testing of current generation system is currently ongoing
- Forward developments include finishing development of partner components and evaluating for use in IRCS next-generation testbed
- Development of a next-generation testbed would enable testing in conditions closer to flight-like
 - More flight-like components
 - Possible vacuum-jacketing of tubing and vacuum-testing of tank



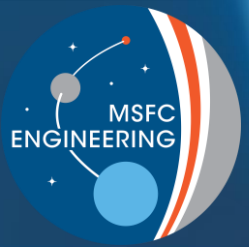
Summary



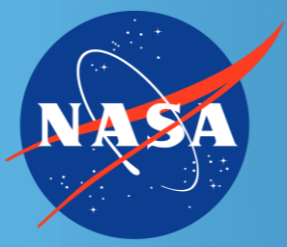
- An Integrated Reaction Control System using a pump-fed pressurized manifold enables a common-fluid approach to spacecraft propulsion, with distinct benefits and challenges relative to other solutions
- The MSFC IRCS team is currently building, testing, and analyzing the performance of the current IRCS testbed
- Key challenges for this system are managing complex pressure transients, limiting heat load from recirculation, and maintaining chill on thrusters
- Several component developments outside of IRCS could provide solutions to these complex problems



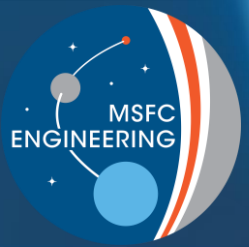
Abstract as Provided



Integrated Reaction Control Systems (IRCS) are considered an enabling technology for future human exploration of the solar system. An IRCS uses the same fuel and oxidizer as the main propulsion system, allowing for increased performance and simplified cryogenic fluid management operations. The IRCS team at Marshall Spaceflight Center is currently evaluating an IRCS system that uses a combination of electric pumps and pressure-regulation devices to provide a constant flow of conditioned propellant to a thruster bank during operation. In the spring 2021 test series presented here, the feasibility of this concept was evaluated using liquid nitrogen as a simulant for liquid oxygen. The goal of this test series was to demonstrate the ability of the pump and pressure regulator to maintain adequate thruster inlet conditions during transient operation.



References



- [1] By NASA/Dimitri Gerondidakis - Public Domain
- [2] Barr, Jon “ADVANCED CRYOGENIC EVOLVED STAGE” May 25, 2018
- [3] Atwell, M., Hurlbert, E., Melcher, R., Morehead, R., “Thermal Vacuum Testing of ICPTA RCS at Plum Brook B-2”, Report JSC-CN-39093. March 30, 2017.
- [4] Case, N., “In-Space Cryogenic Propulsion Development”. Report M18-6853. July 10, 2018.