The Advanced Spacecraft Propulsion and Energy Laboratory

Hyperion-I Phase I: Single Channel Test Readiness Review

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Hyperion-I Campaign Overview

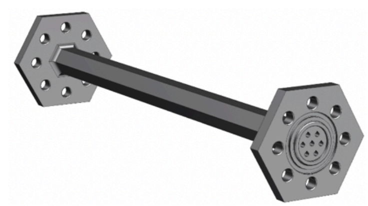
- First engine modeling a solid core nuclear thermal rocket engine
- Additively manufactured metallic core
- Three Phases

Single Channel

- 3/16" OD 316SS Tube
- $D_{hydraulic}$ = 0.090"
- T_{exit} < 350 K

→ Single-Channel Model Validation

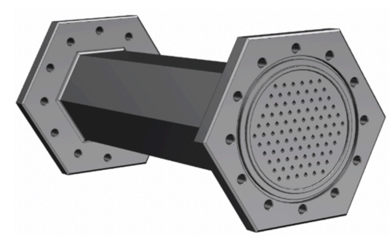
Mid-Scale



- 7 teardrop channels
- $D_{hydraulic}$ = 0.090"
- T_{exit} < 500 K

→ Multi-Channel Model Validation

Full Core



- 61 teardrop channels
- $D_{hydraulic}$ = 0.090"
- T_{exit} = 900 K

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Phase I Overview

Goal: Characterize Heating Behavior

3/16” OD 316 SS tube

- Measure:
    - Propellant ΔT from inlet to outlet
    - Maximum metal temperature
    - Propellant ΔP from inlet to outlet

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Phase I Overview

Comparison to Model Results

- ANSYS multiphysics simulations
  - Maxwell
  - Fluent
  - Steady-State Thermal
  - Transient Thermal
- Phase I experimental results will determine if model needs to be refined for Phases II and III

- Model Setup:
  - T_{inlet} = 300 K
  - P_{inlet} = 500 psig
- Model Predictions:
  - T_{exit} = 339.75 K
  - $T_{metal,max} \approx$ 400 K
  - ΔT = 39.75 K

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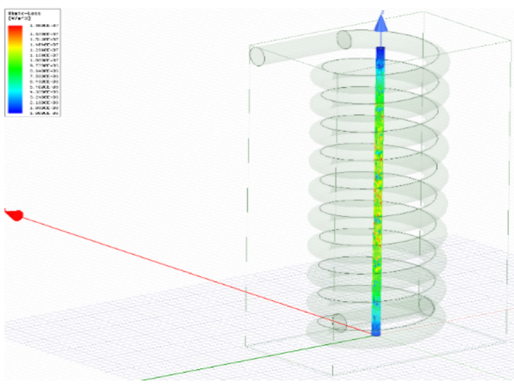
Phase I Overview

Multiphysics Model Structure

Electromagnetic

- ANSYS Maxwell 3D
- Input current limited by in-house induction heater

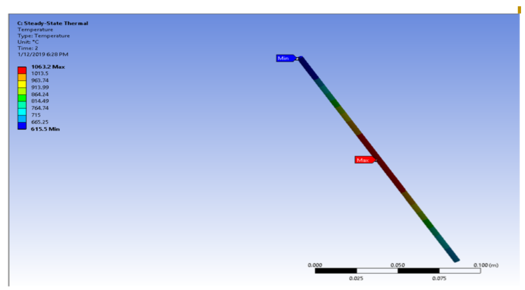


Output

- Ohmic loss contour

Thermal

- ANSYS Transient + Steady State Thermal
- Volumetric heating conditions imported via Maxwell ohmic loss map
- Ambient convection conditions assigned for dry heating tests

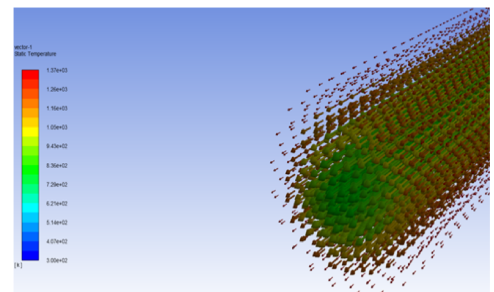


Outputs

- Transient and steady state temperature maps of test article heating without working fluid flow conditions

CFD

- ANSYS FLUENT
- Imports ohmic losses from Maxwell model
- Working fluid pressures assigned at inlet and outlet mesh boundaries
- Assumes thermally insulated test articles



Outputs

- Working fluid outlet conditions
- Steady state test article temperature

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Test Stand Overview

Design Approach

Test Stand Requirements:

- Flow gaseous nitrogen at a rate of up to 0.11 lb/s (90.4 SCFM , 0.05 kg/s)
- Supply nozzle inlet with nitrogen up to 1000 psig
- Supply pressurized nitrogen flow for a total time of 15 min
- Acquire data for temperature, pressure, and thrust throughout system
- Able to relieve the system from high pressures to keep personnel and crucial components safe
- Phase I test requirements will also be discussed
    - Pressure: 500 psig
    - Flow rate: 0.00025kg/s

P&ID

Hyperion-1 Piping and Instrumentation Diagram

Legend

- Gas Bottle
- Pressure Transducer
- Regulator
- Thermocouple
- Ball Valve
- Relief Valve
- Check Valve
- Plenum
- Filter
- Needle Valve
- Solenoid Valve

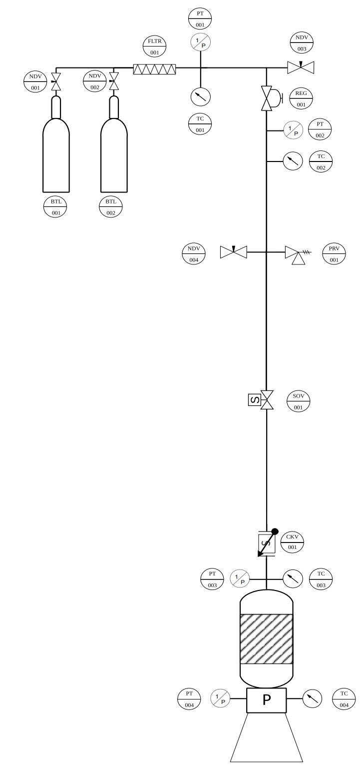
Number Scheme:

AAA-F##

AAA: Acronym
F: Fluid Number
##: Tag Number

AAA	Instrument
FT	Flow Meter
LC	Load Cell
PI	Pressure Indicator
PT	Pressure Transducer
TC	Thermocouple

AAA	Equipment/Component
BTL	Gas Bottle
CMP	Compressor
CKV	Check Valve
FLTR	Filter
HBV	Hand Valve
LVL	Level
NDV	Needle Valve
PBV	Pneumatic Ball Valve
PMP	Pump
PRV	Pressure Relief Valve
REG	Pressure Regulator
RD	Rupture Disk
SOV	Solenoid Valve
TK	Tank (Atmosphere)
V	Vessel (Pressurized)



Test Stand Overview

Line Sizing

- Conditions:
  - Gas – Nitrogen
  - Pressure – 1000 psig
  - Flow Rate – 0.11 lb/s (0.05 kg/s)

•¼'' line was chosen for facilitated routing and lower-cost components
•5 ft of ¼'' line, total pressure drop is 45 psig across the system.

Line Size [in]	Pressure Drop [psi/ft]
1”	0.003
3/4”	0.01
1/2”	0.12
3/8”	0.51
1/4”	8.00
1/8”	1200

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Test Stand Overview

Pressure Regulator

<u>Requirement:</u>

- 1000 psig at exit plenum and flow rate of 90.4 SCFM

Tescom 44-1300 Series

- $C_v = 0.8$
- Max Inlet Pressure : 3500 psig
- Max Outlet Pressure : 1500 psig

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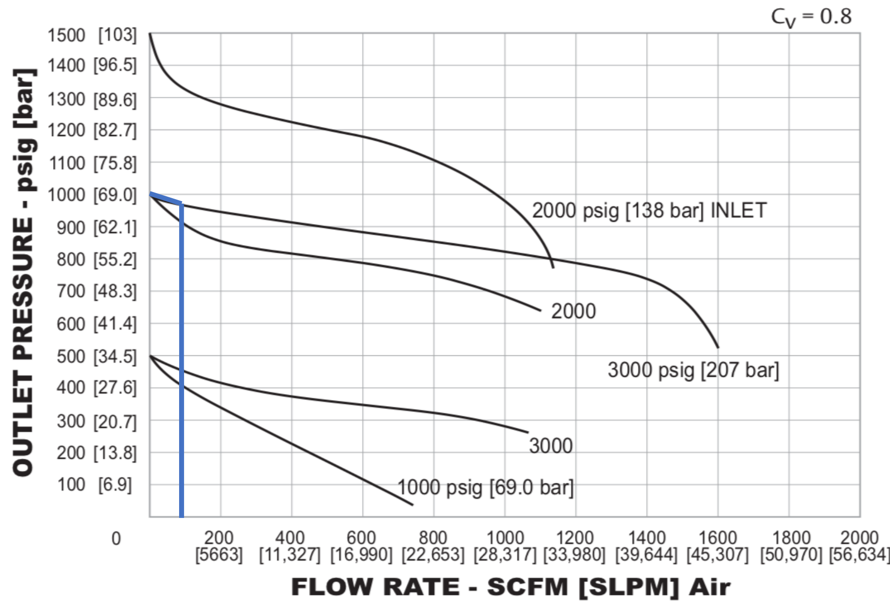
Test Stand Overview

Tescom 44-1300 Flow Curves

Flow Conditions:
- 2640 Inlet Pressure
- 1000 Outlet Pressure

Flow Results:
- Flow Rate: 90.4 SCFM
- Pressure Droop: ~ 40 psig
- Regulator is able to produce desired flow

Phase 1 Conditions
- 2640 Inlet Pressure
- 500 Outlet Pressure
- Flow Rate: 0.45 SCFM
- Flow curves out of test conditions range, expecting minimal pressure droop.



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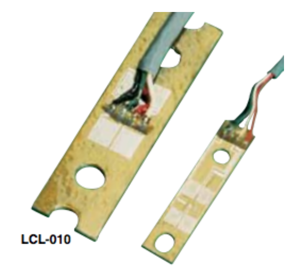
Test Stand Overview

Instrumentation

- Pressure Transducers:
  - Omega PX309-3KG5V
  - 0 to 3000 psig
  - Accuracy: 0.5 %
  - ¼'' NPT

- Thermocouples:
  - K-Type Omega KMQXL
  - Max Temp: 2440 °F (Exit Plenum Temp: 1340 °F)
  - ¼'' Diameter

- Load Cell
  - Omega Thin Beam Load Cell LCL-040
  - Low Range Capacity: 0 - 40 lb (170 N)



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Test Stand Overview

Mass Flow Measurement (Phase 1 & 2)

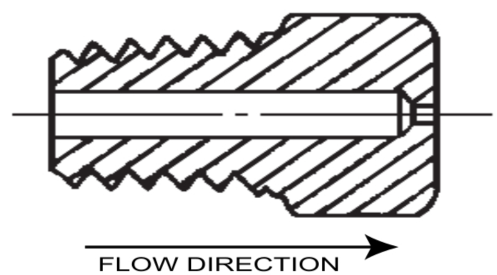
Calculated orifice size with choked flow equation for a compressible fluid

- $d = 9.62\ x\ 10^{-9}\ m = 0.01\ in$
- $P_0 = 500\ psi$ = 3346025.7 Pa
- $C_d = 0.61$ (Sharp Edge Orifice)
- Nitrogen Properties:
  - $\gamma = 1.4$
  - $\rho = 39.72\ \text{kg}/m^3$
- $A = 7.27\ x\ 10^9\ m^2$
- $\dot{m} = 0.00025 \frac{kg}{s}$

$$\dot{m} = C_d A \sqrt{\gamma \rho_0 P_0 \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{\gamma-1}}}$$

O’Keefe Controls Co. EM-10-BR Orifice

- 0.01’’ Outlet
- Max Pressure: 4000 psi



Test Stand Overview

Mass Flow Measurement (Phase III)

- Ideal gas flow through rocket nozzle equation:

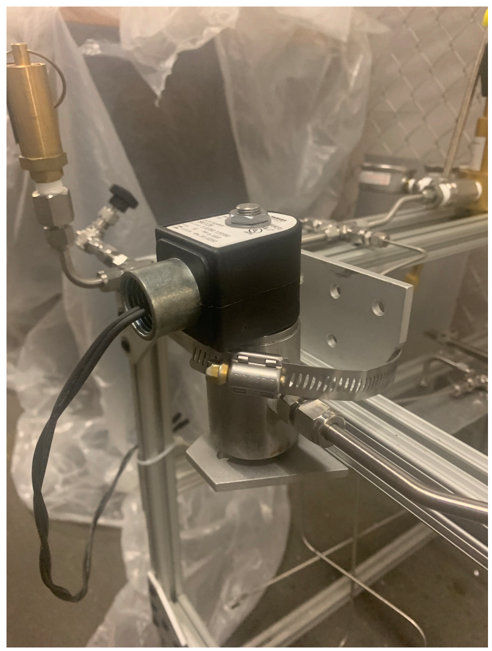
$$\dot{m} = A_t P_0 \sqrt{g\gamma \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{\gamma-1}} / RT}$$

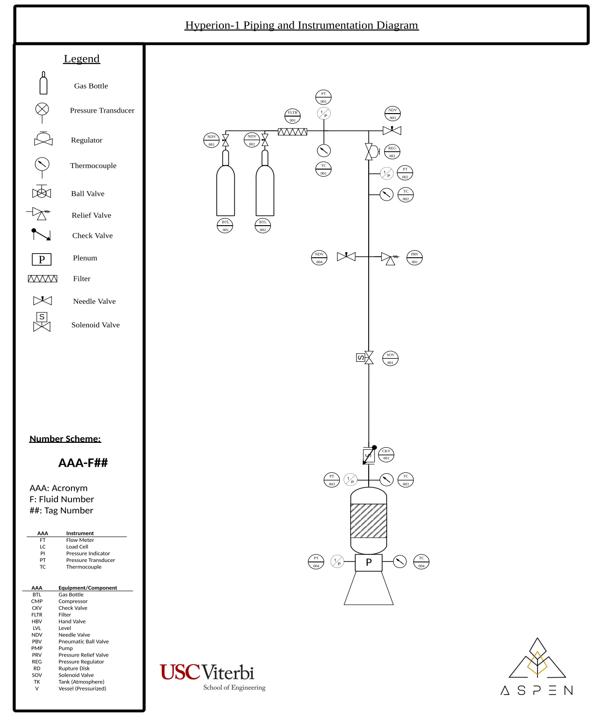
- A_t, Nozzle throat area
- P_0, upstream pressure
- g, gravitational constant
- γ, specific heat ratio
- R, gas constant
- T, total temperature

Test Stand Overview

Post Feed System Peer Design Review (Dec. 7th, 2018)

- Orientation of solenoid valve was changed to an upright position
- Relief valve positioned with the relief side facing up





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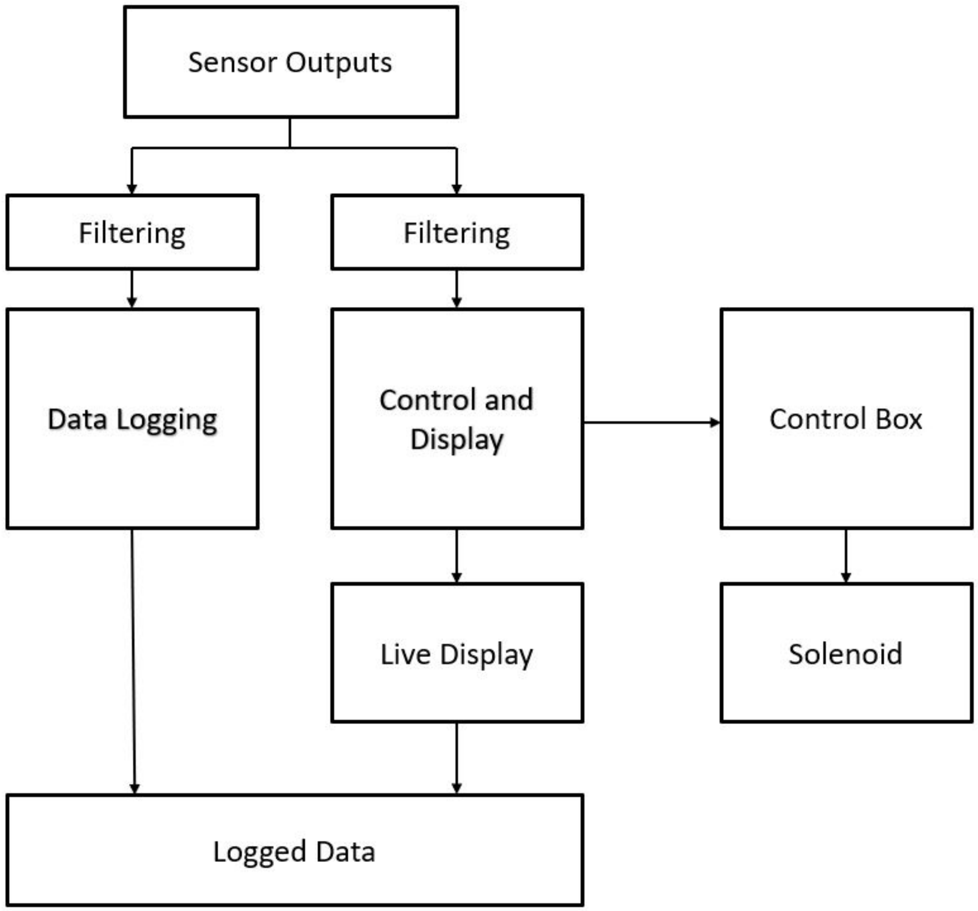
DAQ Overview



DAQ Overview

DAQ Capabilities

ASPEN selected the Texas Instruments MSP432P401R for logging and control systems

Hardware Capacity Per Board:

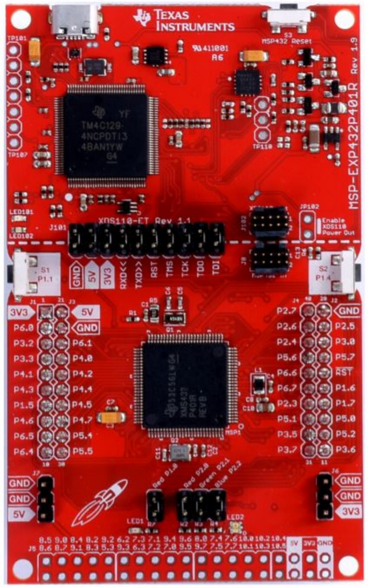
- SAR Precision ADC with 16-bit performance
- 48MHz 32-bit ARM Cortex
- Memory: 256KB Flash, 64KB RAM
- Communication: Up to 4 I2C, 8 SPI, 4 UART

Overall Hardware Capacity:

- 9 current inputs/ 14 total possible
- 600Hz logging rate
- 12kHz Low pass filtering
- Onboard 12V low noise power supply
- 2 current solenoid control outputs/ 4 total possible
- Modular design, allows for easy and cheap board swapping for rapid iteration

Software Capacity:

- Backend based in python, allows for multiprocessing and subprocess generation
- Embedded systems based in C



MSP432P401R

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DAQ Overview

Current Status

Hardware:

- 4 Thermocouples/4 Pressure Transducers Wired, Ninth input left open
- Two MSP432P401R boards installed with input shields attached
- Power supply Installed
- Inputs and shielding installed

Software:

- Logging and Control scripts are running
- Live display running

Challenges Still to Finish:

- Live graphing has slight delay to new data being displayed
- Automated testing in still in the works
- 60Hz resonance is present, working on grounding shielding
- Resolve PT calibration offset errors

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Feed System Qualification

General Overview

- Completion necessary before commencing Hot Flow testing
- Ensures that the feed system and its components will hold pressure at the Maximum Expected Operating Pressure and to pressures exceeding this (Proof Pressure)
- Single Qualification Test:
  - Gas Leak/Proof with gaseous nitrogen

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Feed System Qualification

Safety and Certifications

- General Lab Safety Training
- Pressurized System Briefing for all Testing Technicians
- Test stand sandbagged in place

Required PPE	Safety glasses Long pants Closed-toe shoes Ear plugs

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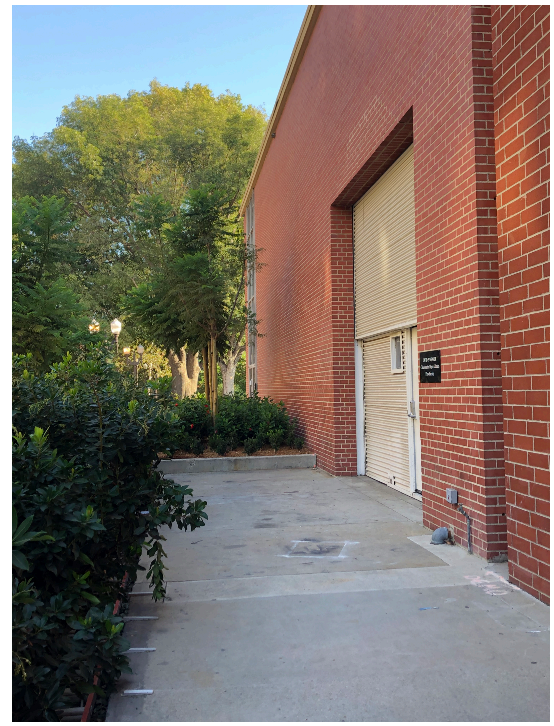
Feed System Qualification

Operations

- Hot Work Permit for RRB Loading Dock
  - Good for one year
- Ordered both gaseous nitrogen tanks (size K) three days in advance
  - Readily available from USC facilities
  - Delivered to AME Offices in RRB 101
  - $13 per month for each bottle



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Feed System Qualification

Operations

- Three primary roles during testing
  - Test Director
    - Test operation authority
    - Approves and directs procedural steps
  - DAQ Operator
    - Runs data acquisition program and actuates valves
    - Monitors leak rate during Leak Test and watches for unusual pressures
  - Technician
    - Operates pressure regulator and find leaks using snoop during Leak Test
    - Tightens any loose fittings

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Feed System Qualification

Gas Leak/Proof Testing

- Ensures all lines and fittings will hold pressure up to:
    - Maximum Expected Operating Pressure (MEOP) : 500 psig
    - Proof Pressure (MEOP*1.5) : 750 psig
- Pressure increased incrementally in Stages
- Feed system isolated in sections starting with component closest to the pressure regulator and moving downstream
- Pressure held at each stage for 3 min
- Leak Rate calculated at each Stage
- System considered proofed when Stage 4 is achieved

MEOP	500 psig
Leak Pressure (1.2*MEOP)	600 psig
Proof Pressure (1.5*MEOP)	750 psig
Stage 1	200 psig
Stage 2	400 psig
Stage 3	600 psig
Stage 4	750 psig

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Feed System Qualification – Gas Leak/Proof Testing

References

- HQ Air Force Space Command Guidance Memorandum for AFSPCMAN 91-710 Volume 6
- NASA Technical Standard: Leak Test Requirements. NASA-STD-7012. 2019.
- Space and Missile Systems Center Standard: Evaluation and Test Requirements for Liquid Rocket Engines. SMC Standard SMC-S-025.

Feed System Qualification – Gas Leak/Proof Testing

Qualification Criterion

- Visual leak observance with snoop during section isolation at each Stage
  - If leaks are present, system is fully depressurized and leaky fittings are tightened
- Leak rate < 3 psig/min at each Stage
  - If leak rate over 3 psig/min then test restarts at Stage 1
  - 3 psig/min leak rate obtained from LPL's November 27th, 2018 Ox-line leak test

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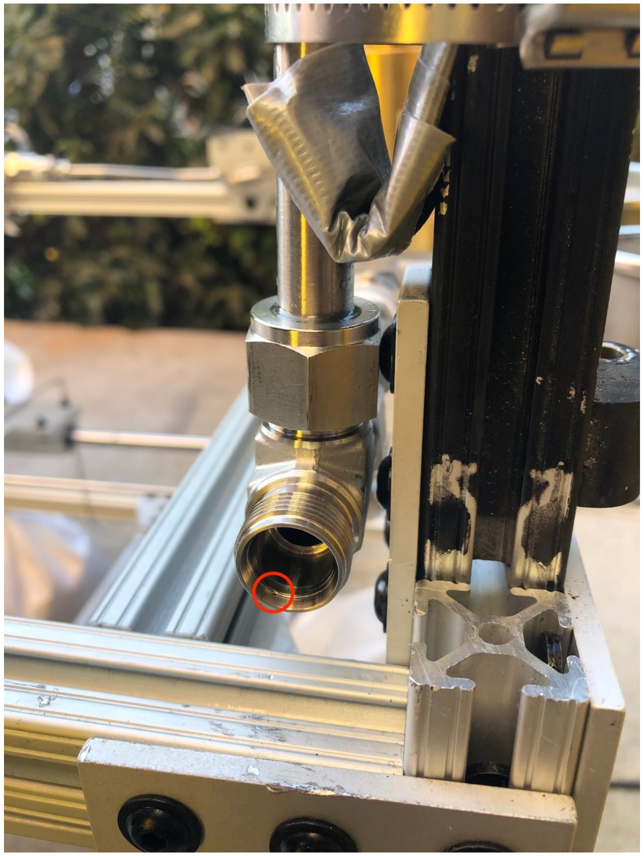
Feed System Qualification – Gas Leak/Proof Testing

Attempt 1

- Test aborted due to scratched T-fitting upstream of the pressure regulator
  - Caused leakage
  - No extra part in lab, so a new one had to be ordered



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Feed System Qualification – Gas Leak/Proof Testing

Attempt 2

Note: Solenoid orientation was switched prior to leak checks

Parameter	Limit
Stage Pressure	200 psig
Max Pressure Reached	210 psig
Average Leak Rate	-0.66 psig/min

Parameter	Limit
Stage Pressure	400 psig
Max Pressure Reached	388 psig
Average Leak Rate	-1 psig/min

Parameter	Limit
Stage Pressure	600 psig
Max Pressure Reached	618 psig
Average Leak Rate	2.72 psig/min

Parameter	Limit
Stage Pressure	750 psig
Max Pressure Reached	762 psig
Average Leak Rate	1.21 psig/min

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Feed System Qualification – Gas Leak/Proof Testing

Lessons Learned & Feedback Received Post-Testing

- Need a cart to carry DAQ and organize wires
- Relief valve should be below Proof Pressure (750 psig)
  - During Leak/Proof it should be plugged somehow…

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Hot Flow

General Overview

- Purpose of obtaining temperature and pressure measurements to compare against ANSYS Multiphysics model results
- ANSYS model predicts ~10 min for dry heating steady state thermal
  - Used to determine experiment run time
- Heater turned on upon opening of the primary solenoid

Operating Pressure	500 psig
Heater Setting	300 A
Testing Period	10 min

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Hot Flow

Safety and Certifications

- General Lab Safety Training
- Pressurized System Briefing for all Testing Technicians
- USC EH&S General Lab Safety Training
- Class A and Class C Fire Extinguisher available
- Faraday cage for electromagnetic radiation containment
- Fire Department notified of testing
- Cones set up around Loading Dock and sidewalk
- Test stand and cylinders sandbagged in place

A		Ordinary Combustibles	Wood, Paper, Cloth, Etc.
B		Flammable Liquids	Grease, Oil, Paint, Solvents
C		Live Electrical Equipment	Electrical Panel, Motor, Wiring, Etc.
D		Combustible Metal	Magnesium, Aluminum, Etc.
K		Commercial Cooking Equipment	Cooking Oils, Animal Fats, Vegetable Oils

Required PPE	Safety glasses Long pants Closed-toe shoes Ear plugs

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Hot Flow

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Hot Flow

Operations

- Three primary roles during testing
  - Test Director
    - Test operation authority
    - Approves and directs procedural steps.
    - Depressurizes system
  - DAQ Operator
    - Runs data acquisition program and actuates valves
    - Watches for unusual pressures and other anomalies in the data
  - Technician
    - Sets heater to proper amperage
    - Sets regulator to operating pressure

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Hot Flow

Refinements to Operations after Leak/Proof Testing

- Added a Crew Chief position upon Advisor recommendation
  - Oversee all testing operations are running smoothly and correctly
- Included additional gas cylinder safety and logistics information for more streamlined setup and disassembly
- Setup cones around the loading dock and adjacent sidewalk
- Include more emergency shutdown procedures
- Thermal Camera to continuously metal temp of single channel test article

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Phase I Completion

- Comparison of DAQ experimental data to ANSYS multiphysics models
- White paper on results
- Presentation at NETS (Nuclear and Emerging Technologies for Space)
  - April 6-10 in Knoxville, Tennessee
  - Sponsored by Oakridge National Laboratory
- 2020 AIAA Propulsion and Energy Conference
  - August 24-26 in New Orleans, Louisiana
- Refine methodology for Phase II Hot Flow Testing

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