Development Testing of the Gateway Integrated Bipropellant Refueling Subsystem

Adela D. Han, Brian S. Lusby

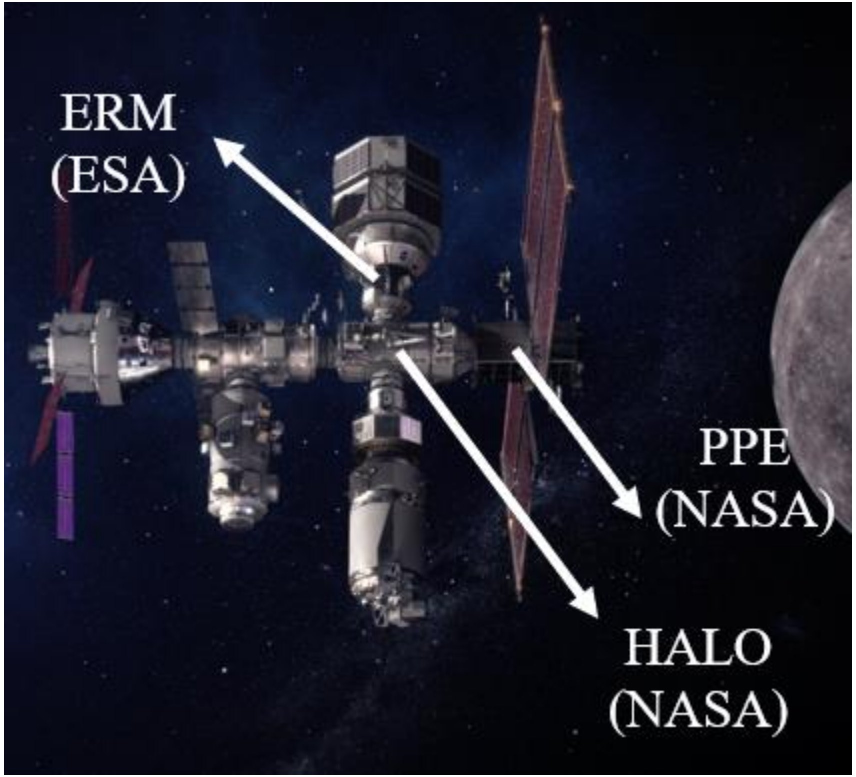
NASA Johnson Space Center/Propulsion Systems Branch

AIAA SciTech, January 11, 2024

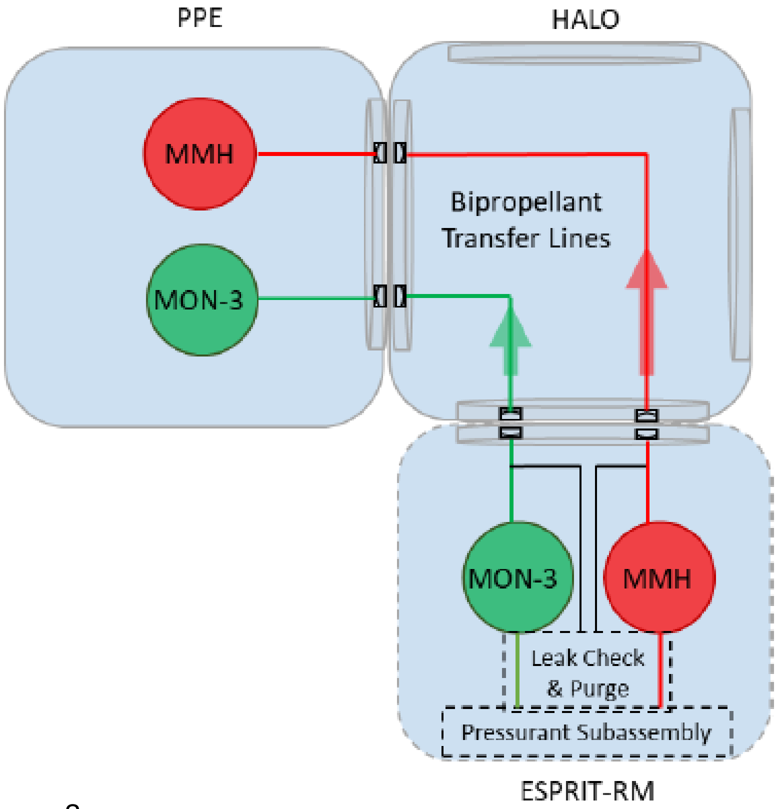
Gateway

- Moon orbiting space station being developed by NASA in partnership with ESA and other domestic and international partners.

- PPE Module Includes MMH and MON-3 (a type of NTO) Bipropellant RCS for Gateway.



RCS Propellant Refueling



- MMH and MON-3 are refueled from ERM through HALO to PPE.

Integrated Breadboard Test Approach

- Refueling Risk: Pressure transient exceeding maximum design pressure during priming and refueling pause.

- Test Objective: To identify and reduce known and unknown risks by simulating refueling operations on the integrated developmental test system called breadboard, collaborating with Thales Alenia Space UK.
  - Thales Alenia Space UK supports ESA on ERM RCS refueling design.

Simulants

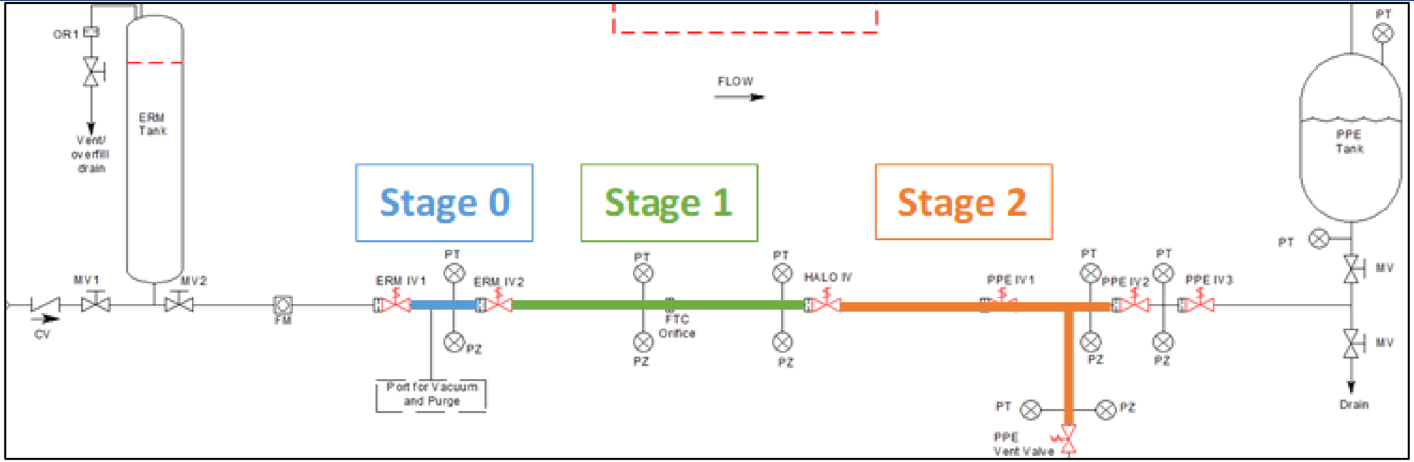
	MMH	Water	NTO	HFE-7100
Vapor Pressure (psia)	0.96	0.46	17.38	3.90
ρ , Density (lb/ft3)	54.3	62.2	89.5	94.4
a , Speed of Sound (ft/s)	5079	4911	3205	1942
Viscosity (cP)	0.78	0.89	0.40	0.58

$$\Delta P_J = -\rho \; a \, \Delta v$$

ΔP_J = *transient pressure change*
ρ = *density*
a = speed of sound in a fluid
Δv = velocity change

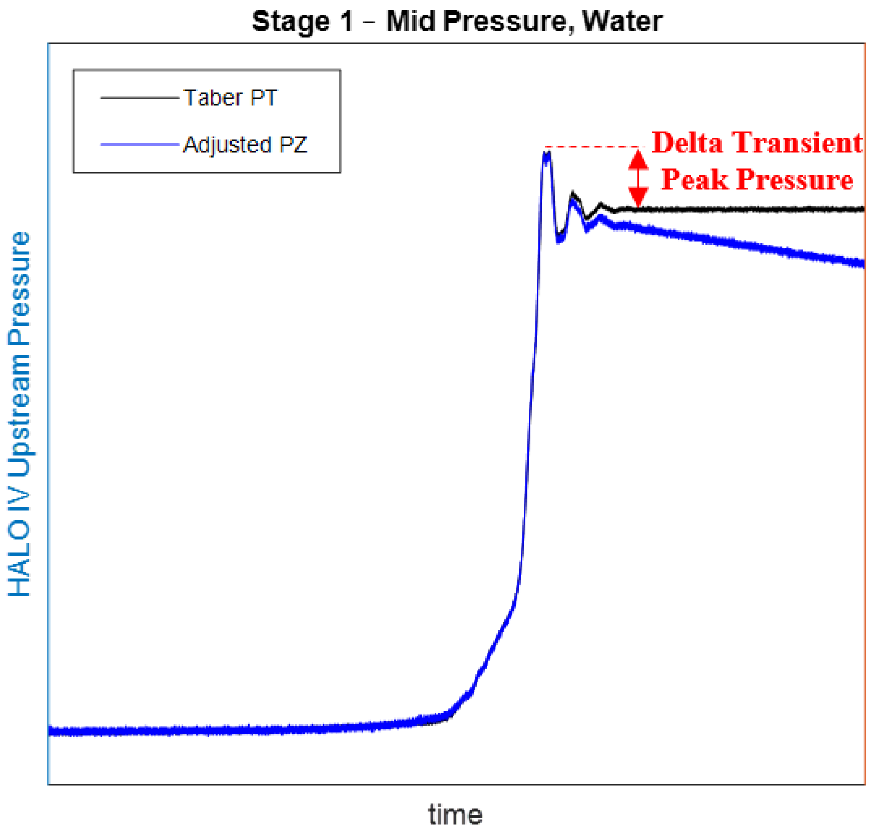
Test System at Thales Alenia Space UK Lab

Priming Test Description



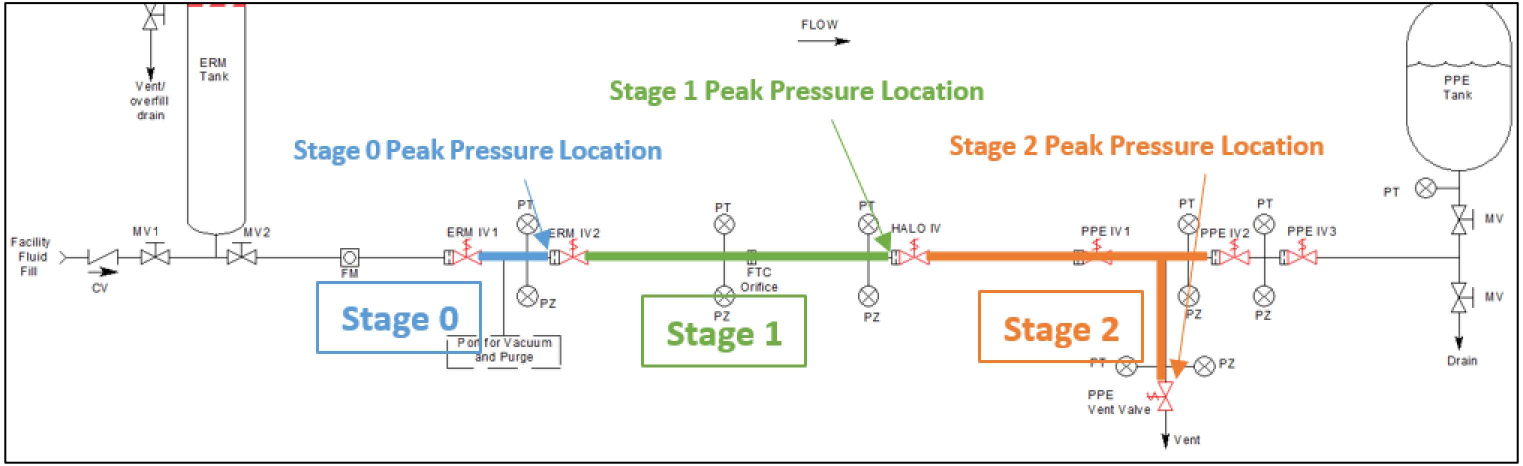
- Primed by IV opening, that isolated pressurized simulant and vacuum line.
- High, medium, and low pressure cases were tested with water.
- Only medium and low pressure cases were tested with HFE-7100.
- Two special cases with medium pressure water.
  - Priming to low pressure helium filled line (4~9 psia).
  - Combined stage 1 and 2.

Priming Delta Transient Peak Pressure

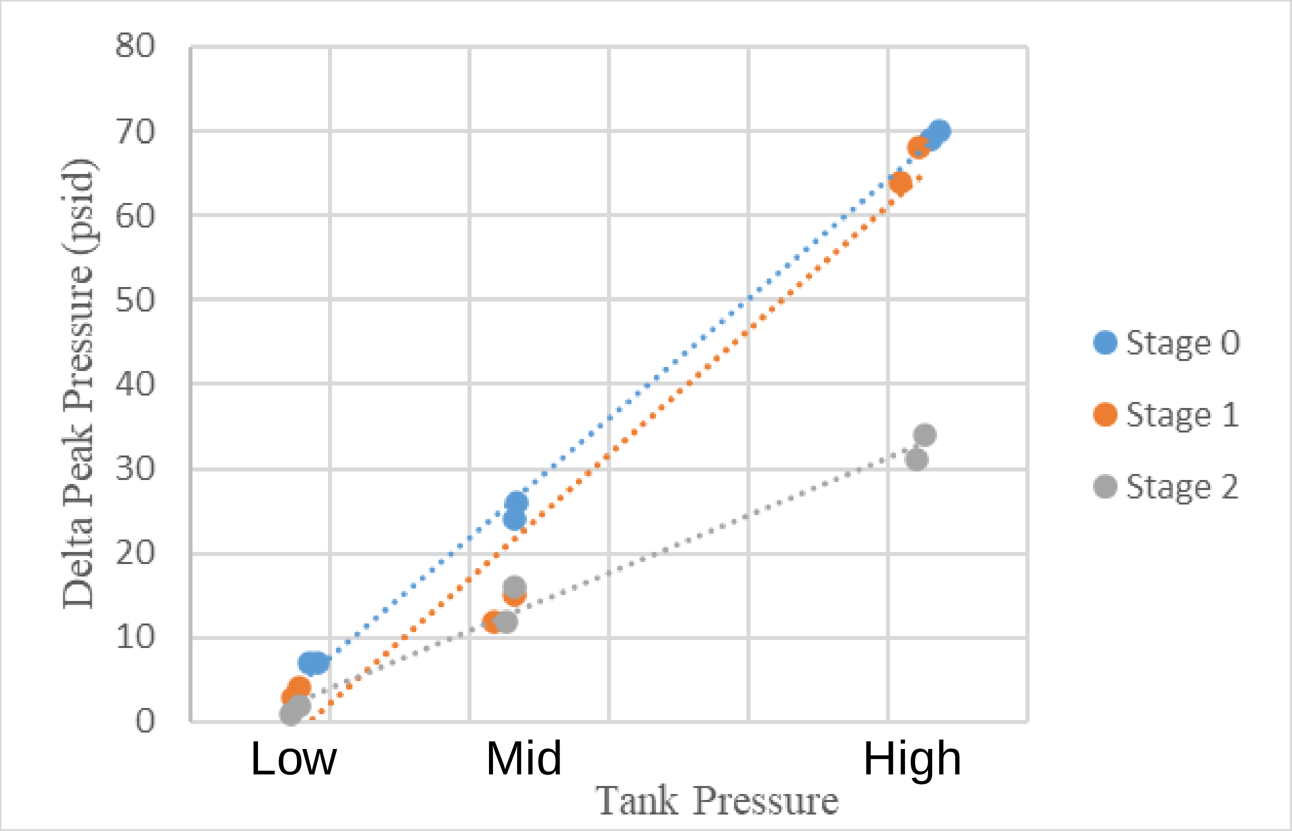


Priming Test Result –Peak Pressure Location

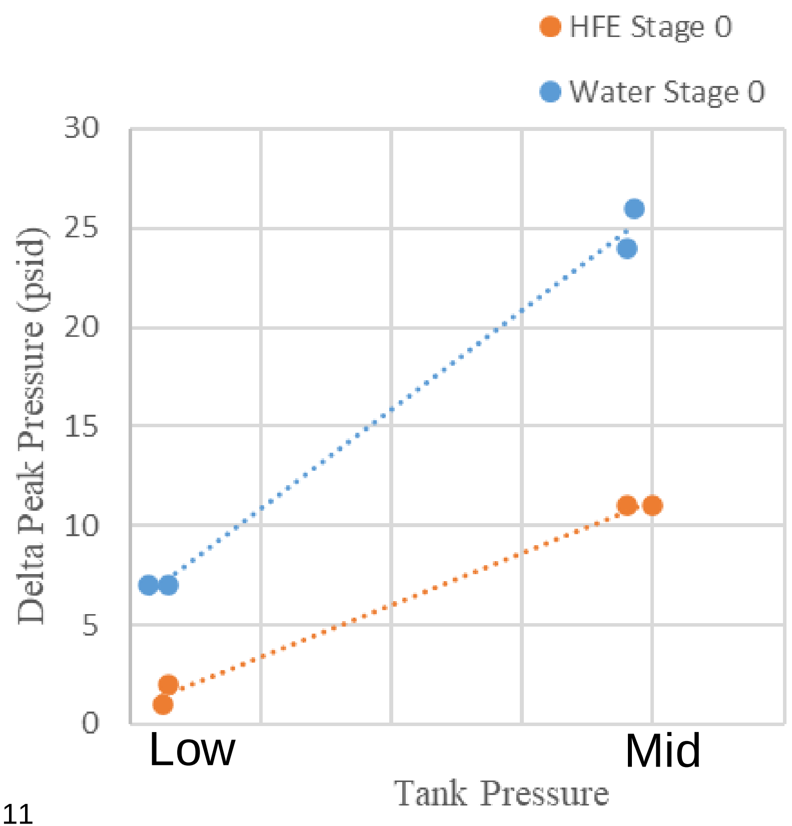
- Generally, highest peak pressure occurred at the upstream of priming volume dead end of a component with low Cv.



Priming Test Result –Tank Pressure



Priming Test Result –Fluid Property



$$\Delta P_J = -\rho\ a\ \Delta v$$

ΔP_J = *transient pressure change*

ρ = *density*

a = *speed of sound in a fluid*

Δv = *velocity change*

Priming Test Result – Other Observations

- Initial line pressure
  - Priming to low pressure helium pressurized lines significantly reduced the pressure transients to almost negligible.
- Distance from ERM Tank
  - The magnitude of the delta peak pressures was generally lower as the priming end gets further downstream from the priming source due to lower flowrate from added flow restriction. Stage 0 > Stage 1 > Stage 2
- Stage 1 and Stage 2 Combined
  - Stage 1 and stage 2 combined priming transient delta peak pressures did not show a significant difference compared to the stage 1 or stage 2.

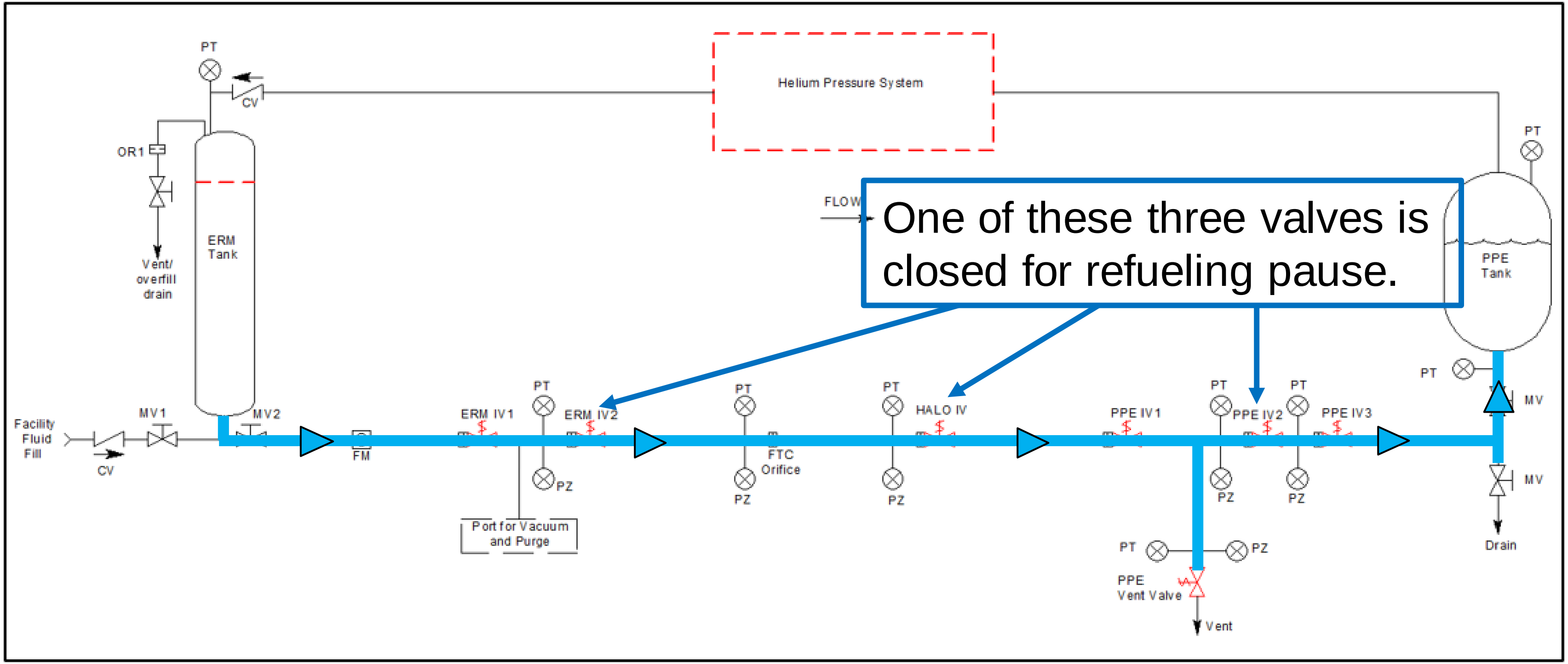
Refueling Pause Test Description

- Refueling line is vacuum primed prior to refueling pause test.

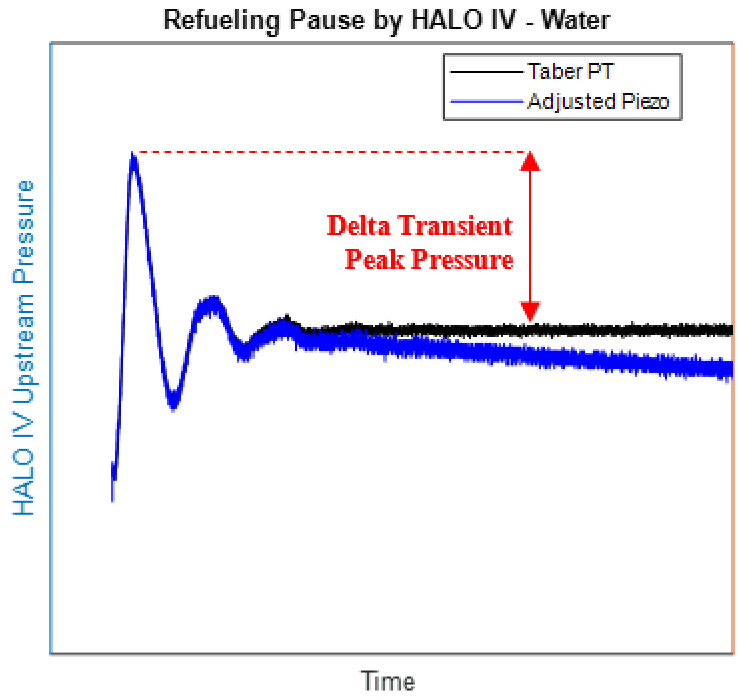
- Target flow rate was achieved by adjusting the ERM tank pressure to set the correct pressure differential between the ERM tank and the PPE tank.
  - ERM tank and PPE tank pressure was not consistent throughout the test cases.

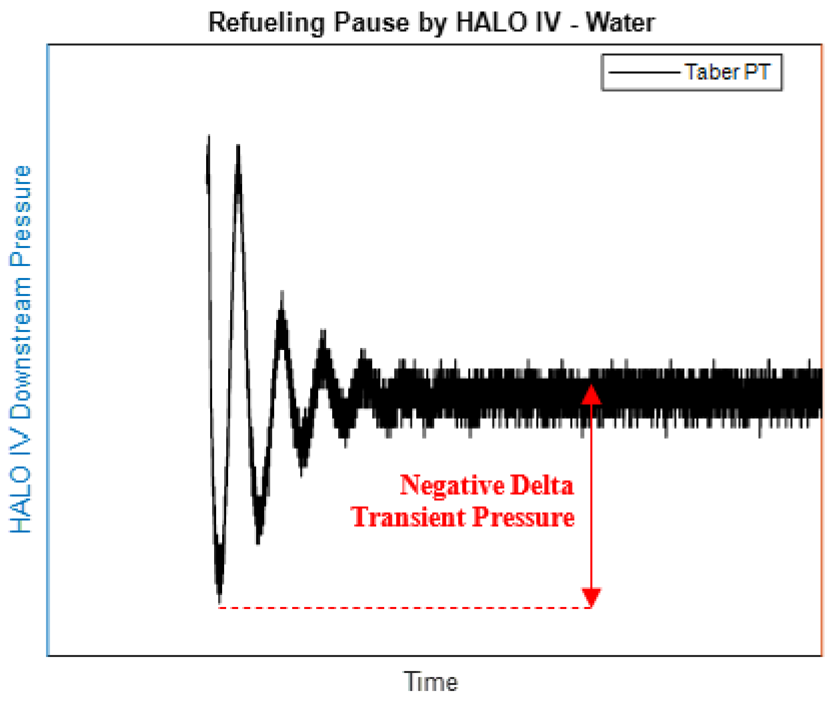
- After steady flow was established one of ERM IV2, HALO, or PPE IV2 was closed.

Refueling Pause Test Description



Refueling Pause Delta Transient Peak Pressure





SHAPING THE FUTURE OF AEROSPACE

Refueling Pause Test Result – General Observations (1)

- Location of Peak Pressure: The highest transient delta peak pressures were observed just upstream of the closing valve.

- Downstream Transient Pressure: Transient pressure drop is more aggressive when the upstream delta peak pressure is higher. The transient pressure drop needs to be evaluated to stay above propellant vapor pressure to avoid vapor collapse.

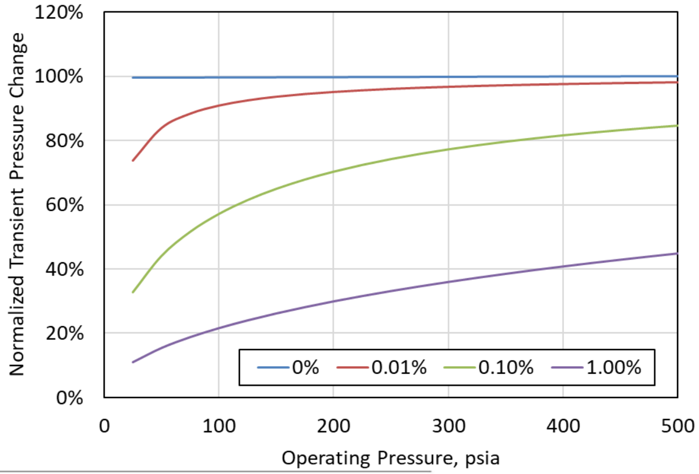
Refueling Pause Test Result – General Observations (2)

- Flow Rate: There were slight deviance of flow rates from each test. The delta peak pressure results from the test cases show that it is highly sensitive to the flow rate.

- Location of Closing Valve: ERM IV2 > HALO IV > PPE. It is observed that the transient pressure will vary depending on the system design around the closing valve and valve closing time.
  - ERM IV2 is a different valve with different Cv and closing time than HALO IV and PPE IV2.

Refueling Pause Test Result – Tank Pressure

- Tank pressure is a sensitive parameter for pressure transients.
- Transient delta peak pressure were observed to be higher when the operating pressures were higher at comparable flow rates.
- Entrained gas has a larger effect at low pressure.
- Engrained gas effect are reduced as the operating pressure increases.



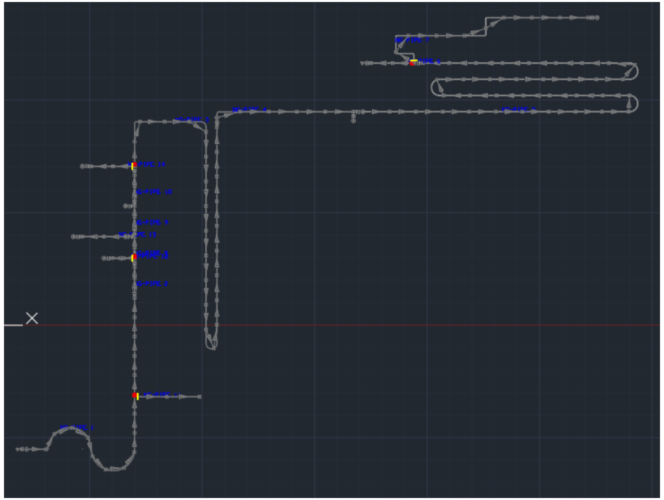
Refueling Pause Test Result – Fluid Property

- Refueling pause data was collected at different tank pressures, fluid impact on delta peak pressure cannot be evaluated with the collected data.

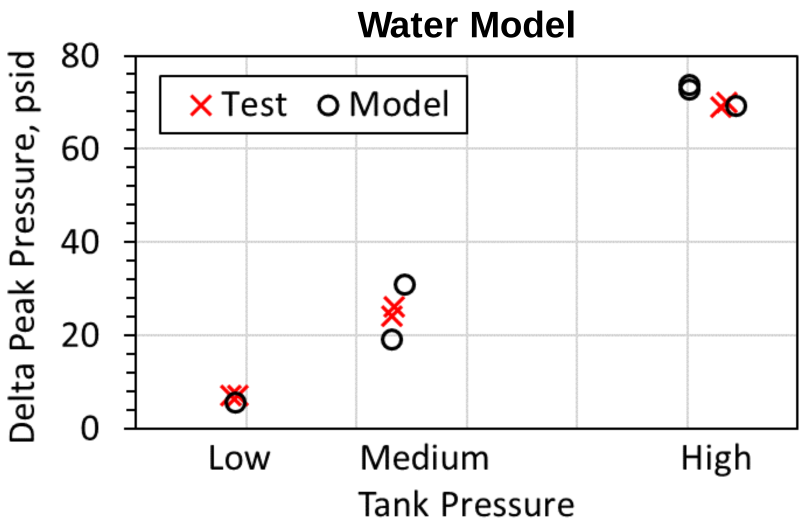
- Delta peak pressure ratio of water to HFE-7100 should be about 2 to 1 at comparable operation pressure and flow rate.
  - Combined effect of density and speed of sound.
  - $\Delta P_J = -\rho\ a\ \Delta v$

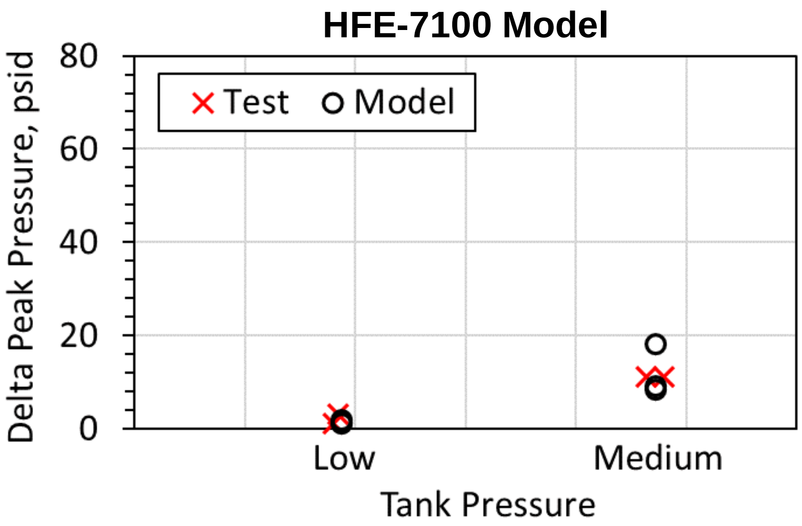
Model Validation Approach

- Thermal Desktop with FloCAD (SINDA/FLUINT Version 6.1)
- Flat-front modeling technique used for priming
- Nonvolatile water (9000 series) and air as perfect gas (8000 series)
- Simplified two-phase HFE-7100 (7000 series)
- Includes liquid compressibility and tube wall compliance
- Assumed temperature of 70°F
- No heat transfer
- Water Model Stats:
  - 14 Pipe Macros
  - 116 Fluid Lumps
  - 106 Flow Paths



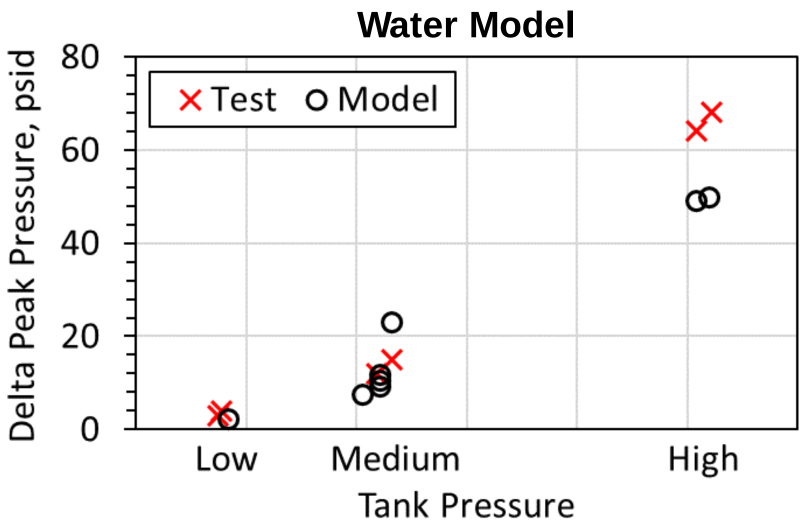
Summary of Stage 0 Priming Results

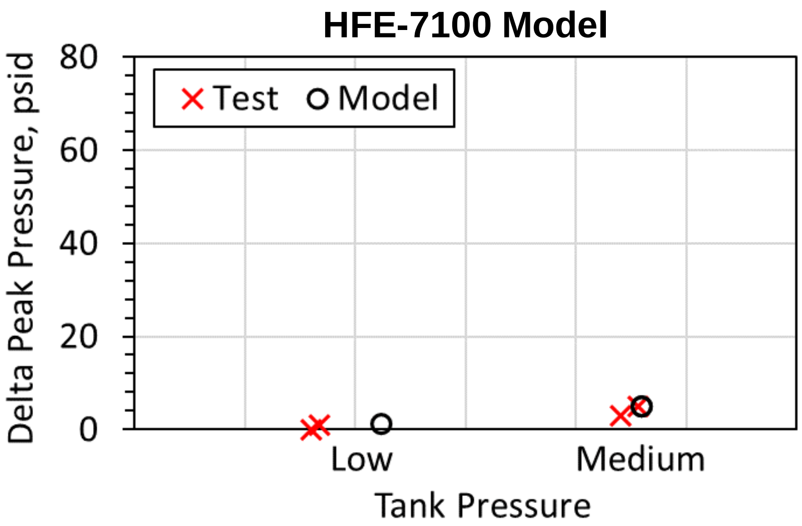




- Model results correlate well with the test data and follow the same trend
- Variability in model results at a given tank pressure is due to slightly different initial vacuum conditions

Summary of Stage 1 Priming Results





- Model results correlate well with the test data for the low and medium tank pressure cases
- Delta peak pressures for the high tank pressure cases tend to be underpredicted, but the difference is close to within the sensor accuracy

Conclusion

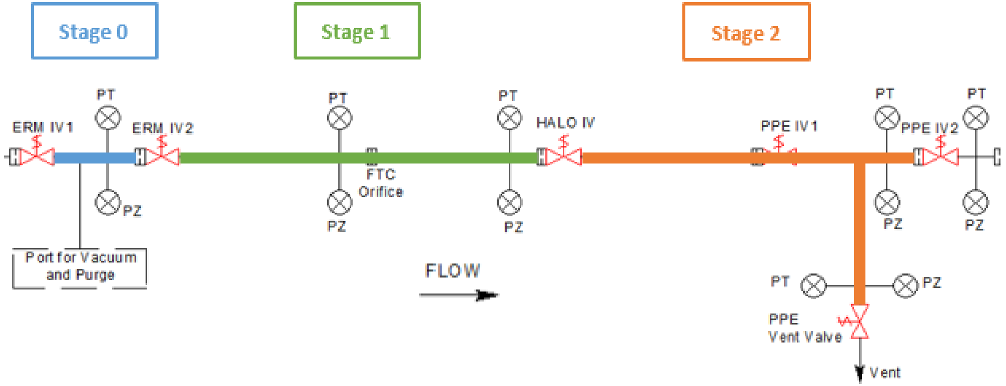
- On-orbit refueling is a developing technology.
- Transient pressure is dependent on various parameter.
  - System Design
  - Operation
  - Fluid Properties
- System needs to be tested and analyzed to ensure successful and safe refueling operation.

AMERICAN INSTITUTE OF
AERONAUTICS AND ASTRONAUTICS

Priming Test Result –Peak Pressure Location (2)

Example Stage 2 – Mid Pressure Priming Delta Peak Pressures

Location	ERM IV2 Upstream	FTC Orifice Upstream	PPE IV2 Upstream	PPE Vent Valve Upstream
Delta Peak Pressure (psid)	12	17	25	31



Refueling Pause Test Cases

Closing Valve	Case Description	ERM Tank Pressure	Actual to Target Flow Rate Ratio
ERM IV2	Water Run 1	Low	1.11
ERM IV2	Water Run 2	Low	1.11
ERM IV2	HFE-7100 Run 1	Mid	1.00
ERM IV2	HFE-7100 Run 2	High	1.14
HALO IV	Water Run 1	Low	1.11
HALO IV	Water Run 2	Low	1.14
HALO IV	HFE-7100 Run 1	Mid	0.99
HALO IV	HFE-7100 Run 2	High	1.00
PPE IV2	Water Run 1	Low	1.11
PPE IV2	Water Run 2	Low	1.17
PPE IV2	HFE-7100 Run 1	Mid	1.00
PPE IV2	HFE-7100 Run 2	High	1.05