

Validation of Transient Spacecraft Refueling Model with Gateway Breadboard Test Data

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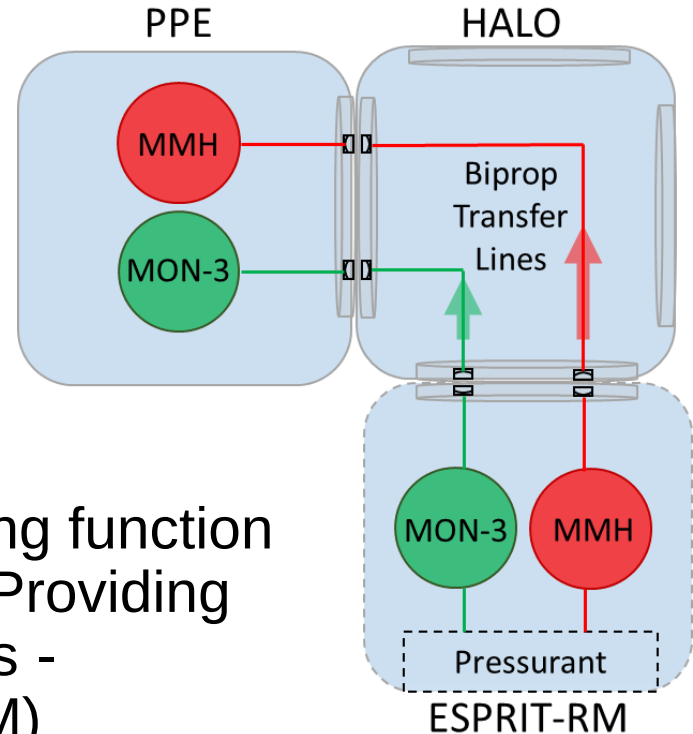
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Introduction

- On-orbit spacecraft refueling is a key enabling technology for deep space human exploration
 - Requires priming liquid propellant into evacuated fluid transfer lines
 - Refueling in stages requires multiple pauses to propellant transfer
- Water hammer surges can exceed pressure limits
- Numerical models can parametrically characterize system performance over a wide range of operating conditions
- Models must be validated with test data to ensure credibility

Lunar Gateway Background

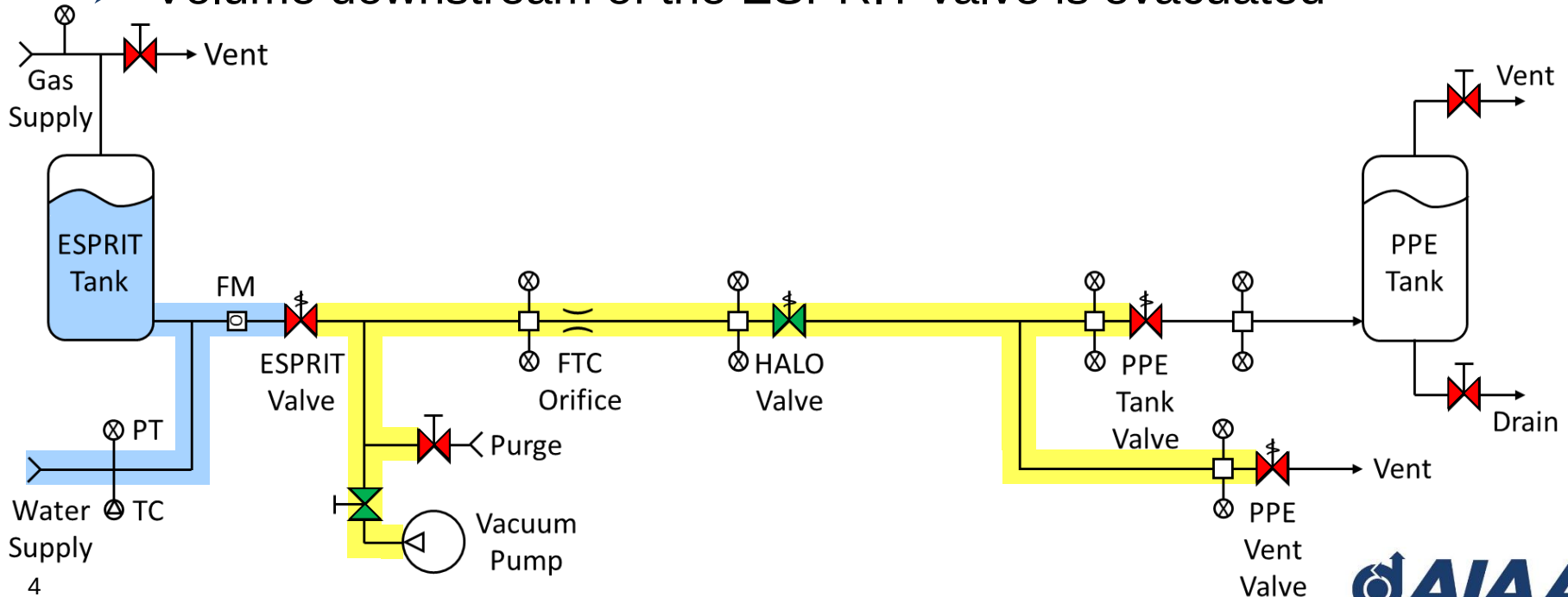
- Deep space orbiting outpost being developed by NASA and ESA
- First two modules:
 - Power and Propulsion Element (PPE)
 - Habitation and Logistics Outpost (HALO)
- Reaction control system (RCS) refueling function will be provided by European System Providing Infrastructure and Telecommunications - Refueller Module (ESPRIT-RM or ERM)



Breadboard Test Operations

➤ Initial Conditions:

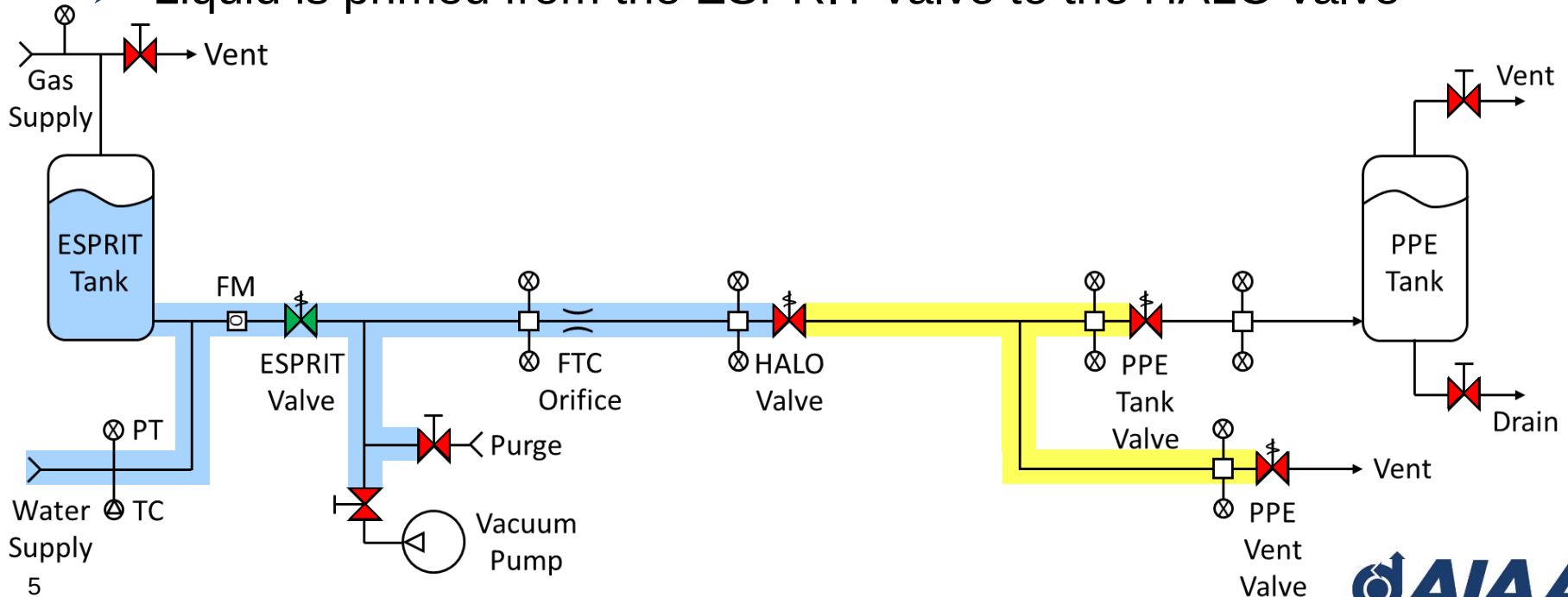
- Volume downstream of the ESPRIT valve is evacuated



Breadboard Test Operations

➤ Stage 1 Priming:

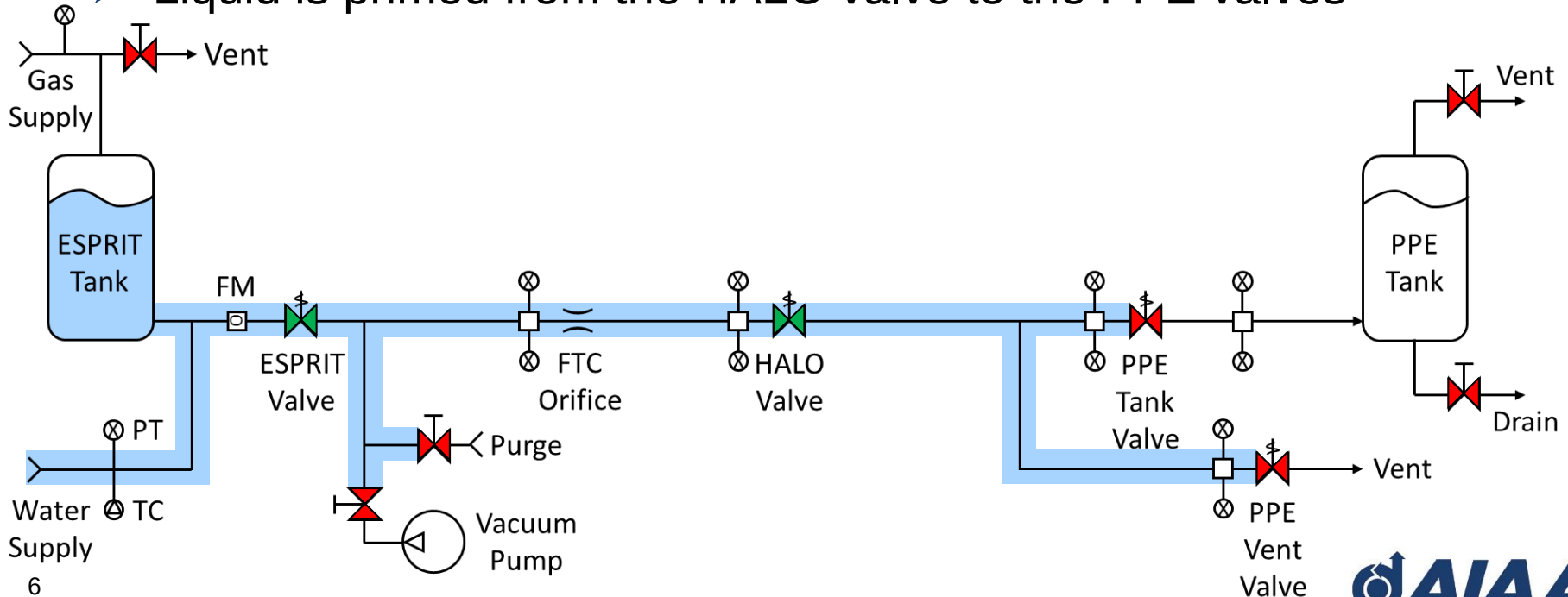
➤ Liquid is primed from the ESPRIT valve to the HALO valve



Breadboard Test Operations

➤ Stage 2 Priming:

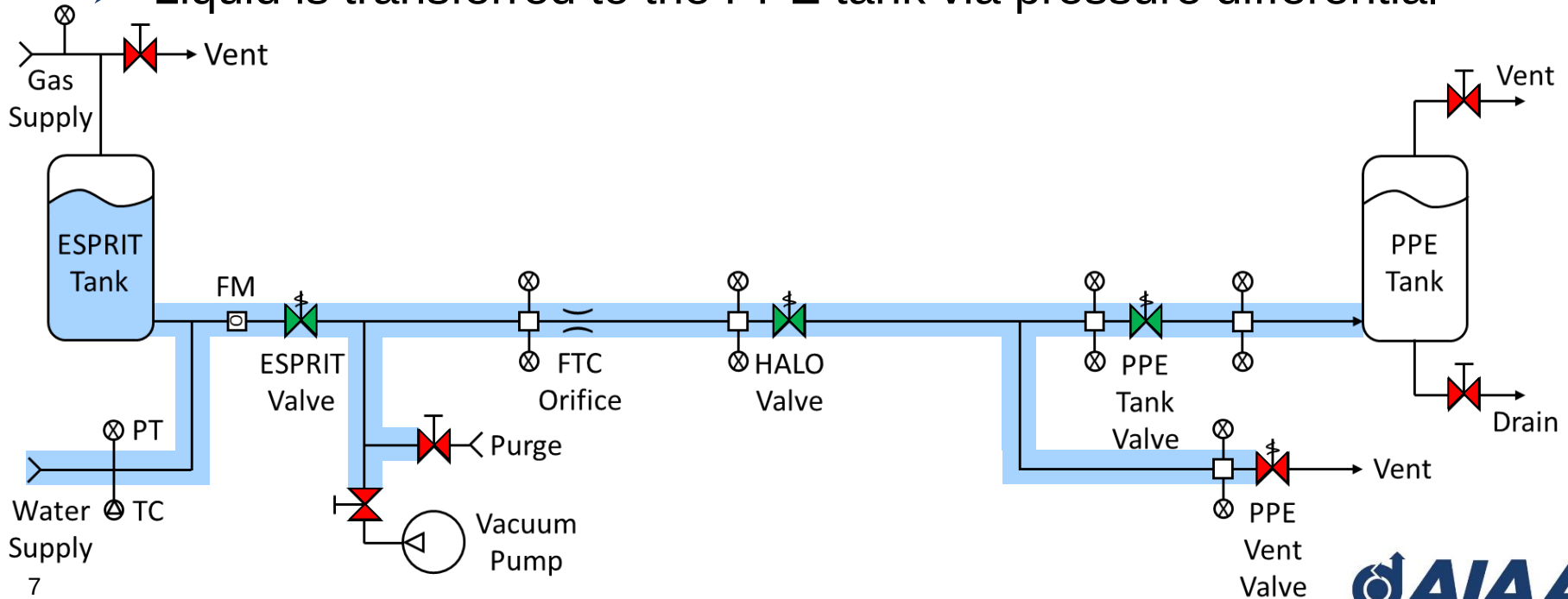
➤ Liquid is primed from the HALO valve to the PPE valves



Breadboard Test Operations

➤ Refueling Begins:

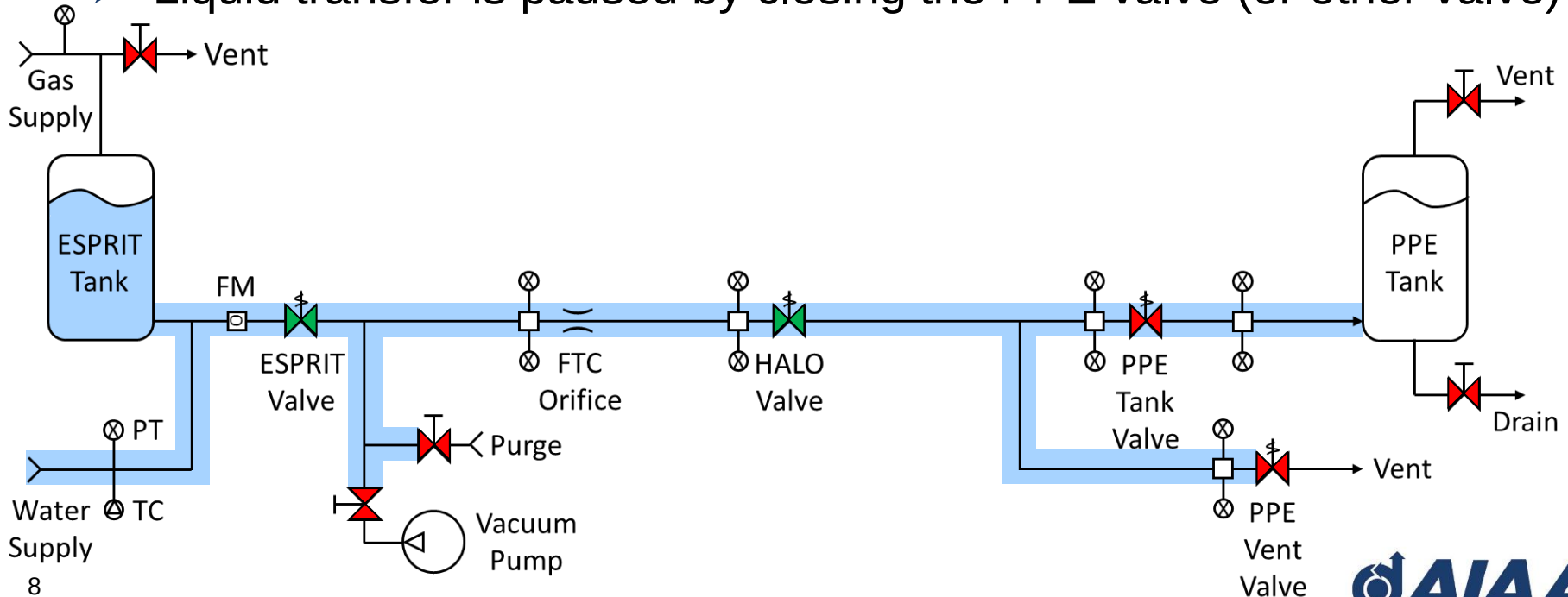
➤ Liquid is transferred to the PPE tank via pressure differential



Breadboard Test Operations

➤ Refueling Pauses:

➤ Liquid transfer is paused by closing the PPE valve (or other valve)

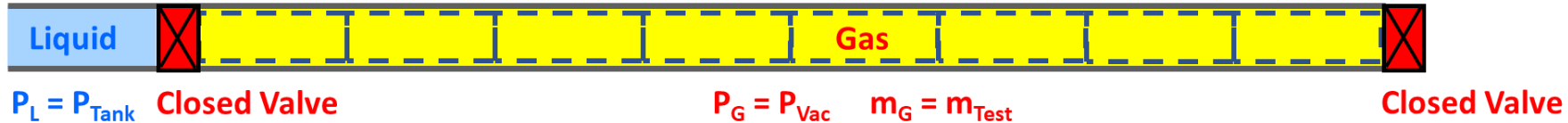


Model Details

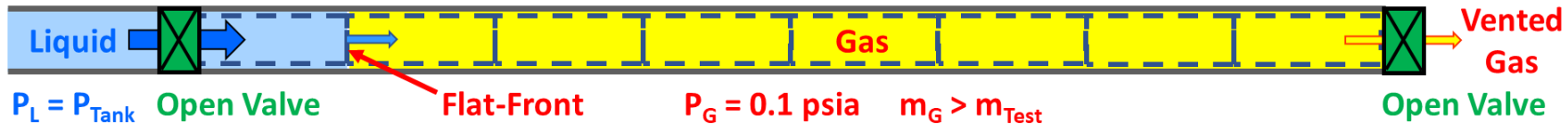
- Thermal Desktop with FloCAD (SINDA/FLUINT Version 6.1)
- Flat-front modeling technique used for priming
- Nonvolatile water (9000 series) and air as perfect gas (8000 series)
- Includes liquid compressibility and tube wall compliance
- Assumed temperature of 70°F
- No heat transfer
- Model Stats:
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

Flat-Front Priming Model Approach

- Initial vacuum pressure is limited to ~ 0.1 psia for numerical stability
- Gas can be “vented” during priming to achieve test conditions



- Liquid begins filling pipe as gas is vented to relieve back pressure
- Flat-front method imposes an axially stratified flow regime



- Gas venting stops just prior to arrival of liquid front



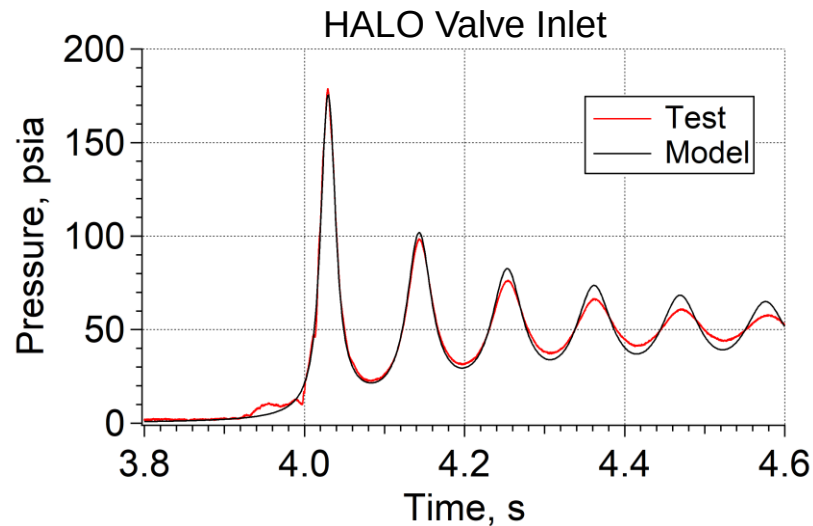
Representative Stage 1 Priming Results

➤ Initial Conditions

	Test	Model
Tank Pressure, psia	53	51
Vacuum Condition, torr	1.0	0.85

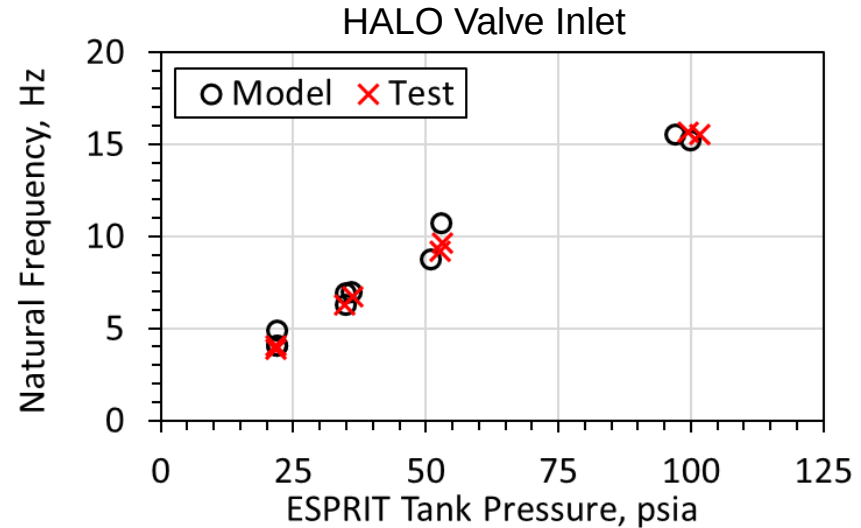
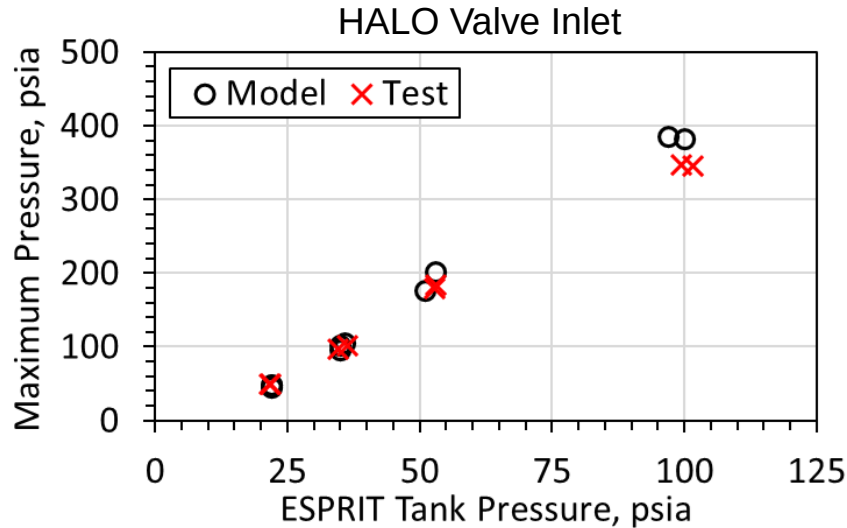
➤ Key Performance Parameters

	Test	Model
Surge Pressure, psia	179	175
Natural Frequency, Hz	9.21	8.77



Model compares very well with test data

Summary of Stage 1 Priming Results



- Surge pressure and natural frequency correlate well with the test data
- Flat-front assumption has larger effect on results at higher tank pressures
- Modeled gas content ranges between 0.74 and 1.0 torr vacuum conditions

Representative Stage 2 Priming Results

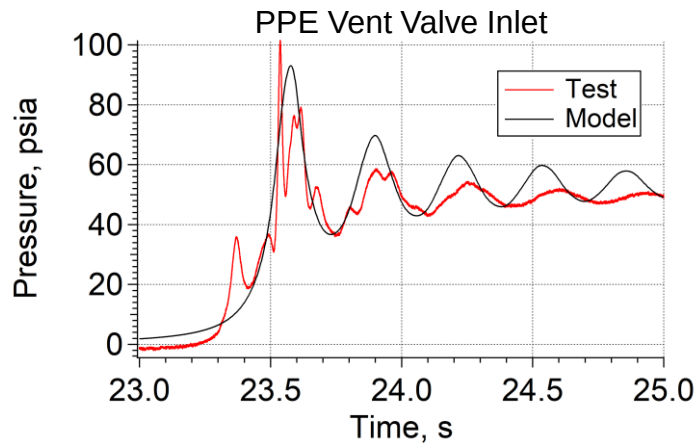
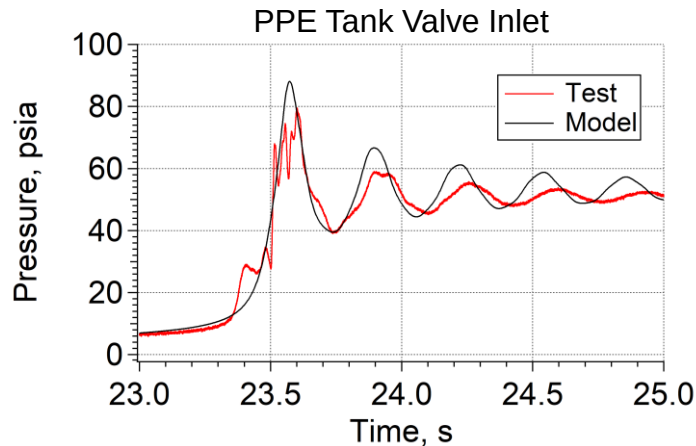
➤ Initial Conditions

	Test	Model
Tank Pressure, psia	53	53
Vacuum Condition, torr	0.6	1.3

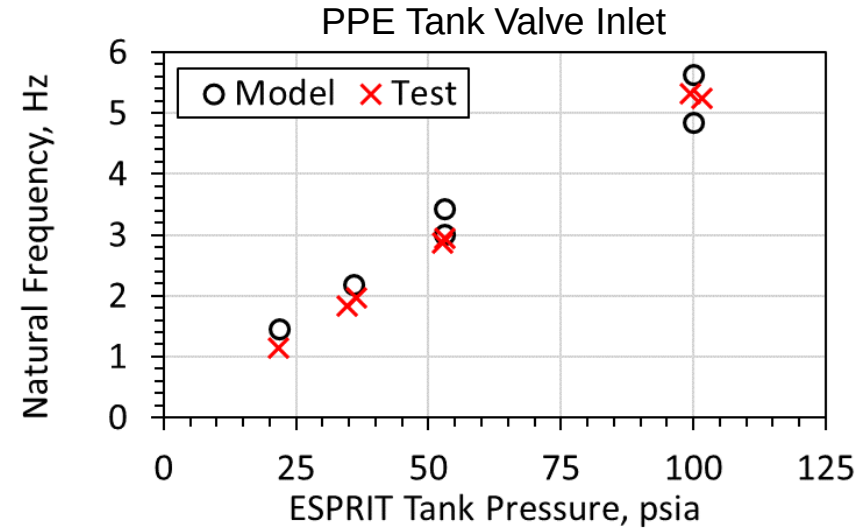
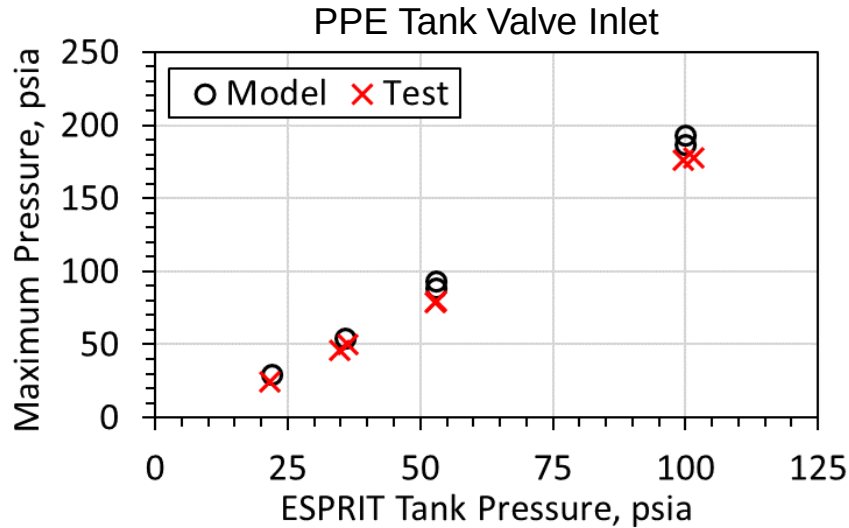
➤ Key Performance Parameters

	Test	Model
Surge Pressure, psia	79	88
Natural Frequency, Hz	2.95	3.01

Surge pressure is higher at PPE vent valve



Summary of Stage 2 Priming Results



- Overpredicted surge pressures correlate with the overpredicted frequencies
- Surge pressures and natural frequencies are lower compared to stage one
- Modeled gas content ranges between 1.1 and 1.3 torr vacuum conditions

Representative PPE Valve Refueling Pause Results

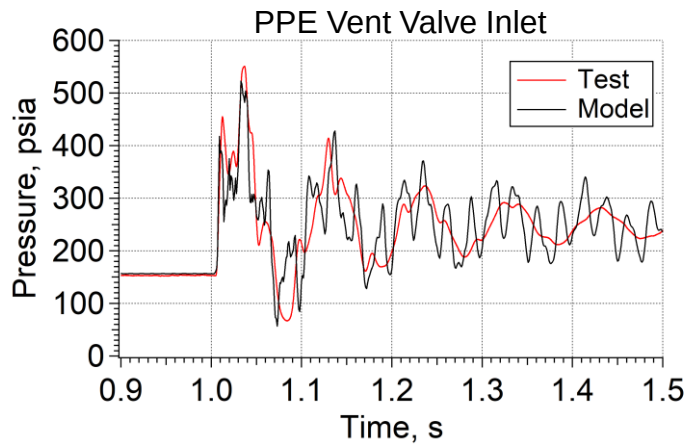
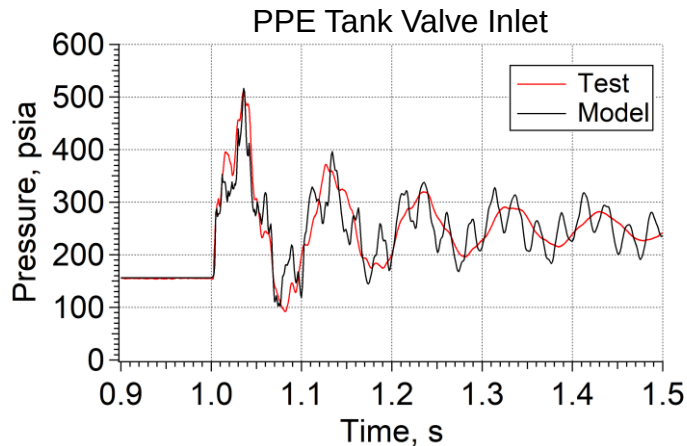
➤ Initial Conditions

	Test	Model
Tank Pressure, psia	252	252
Entrained Gas Fraction	-	0.0002

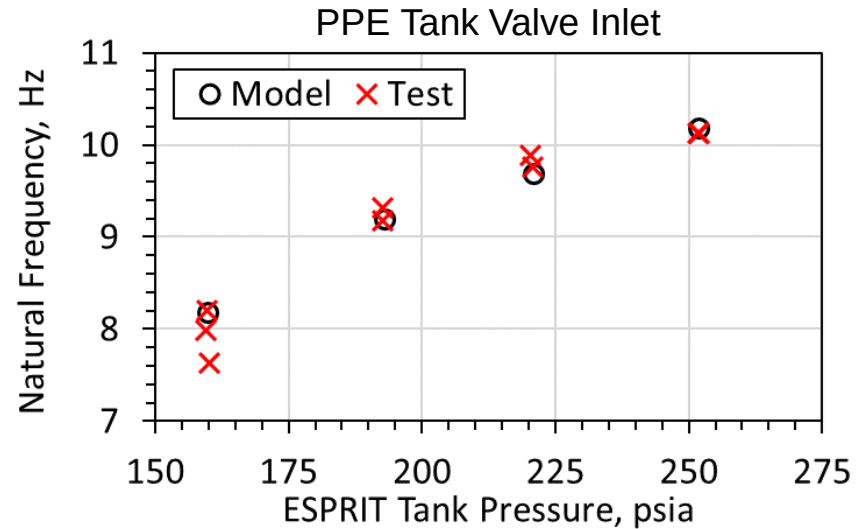
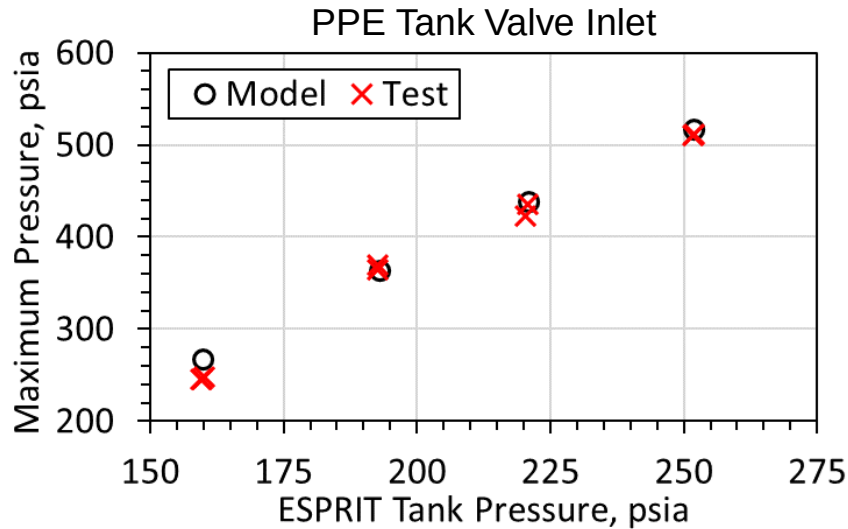
➤ Key Performance Parameters

	Test	Model
Surge Pressure, psia	511	516
Natural Frequency, Hz	10.1	10.2

Secondary frequency mode is more evident



Summary of PPE Valve Refueling Pause Results



- Surge pressure and natural frequency correlate well with the test data
- Modeled entrained gas content ranges between 0.0002 and 0.0008

Conclusion and Forward Work

- Model results have very good agreement with the test data
 - Vacuum priming and refueling pause water hammer surge pressures
 - Natural frequencies
- Additional testing with simulants with our international partners will expand the data set for improved model correlation
- Further risk reduction testing with propellants will fully validate the model, allowing high confidence in flight performance predictions



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