Low Leakage Valves for Long Duration Missions.

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This paper presents a status update on the low leakage cryogenic test valves currently under development at NASA's Marshall Space Flight Center. These valves consist of a 3-inch isolation valve, a 3-inch relief valve, and an 8-inch pre-valve. Each of these valves contain a self-aligning seat and poppet design to significantly reduce the quantity of propellant flowing past the seat when the valve is in its closed state (internal leakage). This self-aligning design utilizes a metallic poppet head with five degrees of freedom and is intended to allow a valve to be more tolerant of the imperfect contacts and misalignments that are commonly found between sealing surfaces. This paper covers the test articles, facilities, objectives, and preliminary results.

I. Nomenclature

A	=	cross-sectional area
C_d	=	discharge coefficient for orifices and nozzles
C_v		flow coefficient for a valve, defined as the volume of water at 60°F that will flow through a valve per minute with a pressure drop of 1 psi across the valve.
GH_e	=	gaseous helium
GN_2	=	gaseous nitrogen
LH_2	=	liquid hydrogen
LN_2	=	liquid nitrogen
m	=	internal mass of propellant loss
$t_{mission}$	=	theoretical mission duration
Q	=	internal leakage rate
ρ_{H2_STP}	=	density of hydrogen at standard temperature and pressure.

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II. Introduction

Current aerospace cryogenic valves present challenges to potential long duration missions that utilize cryogenic propellants. Small interplanetary and long-life communication satellites typically utilize hypergolic propellants that operate at higher temperatures, making it easier to achieve very low internal leakage rates. Larger vehicles for long duration missions will likely need to utilize cryogenic-based chemical and nuclear systems to achieve mission requirements. Some early propulsion concepts are projected to require valves with a nominal size ranging from 3” to 10”.

Cryogenic aerospace valves that are currently available will typically have internal leakage rates which can range from 100 to 300 Standard Cubic Inches per Minute (SCIM) for 3” valves, or upwards of 2,000 SCIM for 10” valves. With just a few of these valves in a system, internal leakage could account for multiple tons of propellant loss over the course of a hypothetical Mars mission, as shown in Fig. 1.

$$\rho_{H2\_STP} := 0.0052089 \frac{lbm}{ft^3} \qquad Q_{typical} := 2000 \frac{in^3}{min} = 546.2 \frac{cm^3}{s}$$

$$t_{mission} := 1\ yr \qquad Q_{goal} := 2.0 \frac{in^3}{min} = 0.546 \frac{cm^3}{s}$$

$$m_{typical\_mission} := Q_{typical} \cdot \rho_{H2\_STP} \cdot t_{mission} = 3170.9\ lbm$$

$$m_{mission\_goal} := Q_{goal} \cdot \rho_{H2\_STP} \cdot t_{mission} = 3.2\ lbm$$

Fig. 1 Potential Propellant Loss Over the Course of a Long Duration Mission

Most internal leakage rates can be attributed to inherent imperfections and misalignments, which result in imperfect contact between sealing surfaces, as shown in Fig. 2.

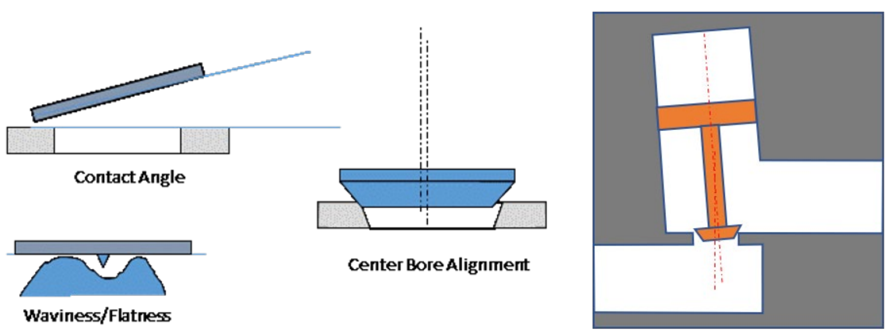

Fig. 2 Imperfections and Misalignments Between Sealing Surfaces

The Valves, Actuators & Ducts Design and Development Branch (ER14) at Marshall Space Flight Center (MSFC) have created a self-aligning seat and poppet design (shown in Fig. 3) that allows a valve to be more tolerant of imperfect contacts. This design utilizes a metallic poppet head with five degrees of freedom that allows the poppet to self-align with the seat, reducing the need for tight tolerances. A spherical poppet and conical seat design is a classic design for poppet valves, but a flexible coupling with load application below the seat contact point is used in order to reduce the potential for non-uniform seat stress associated with misalignment.

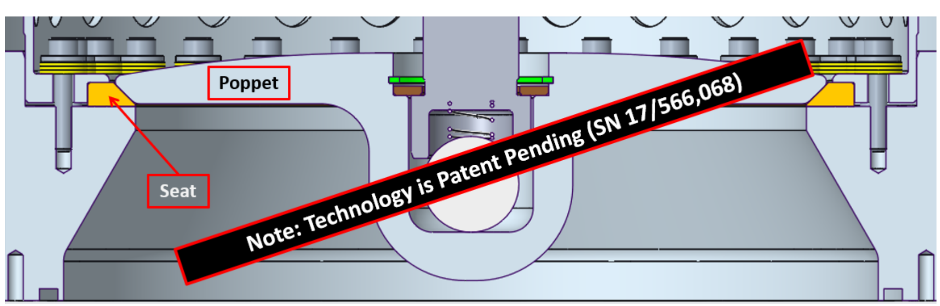

Fig. 3 Self-Aligning Seat and Poppet Design

ER14 have previously developed and tested other proof-of-concept development rigs to prove the self-aligning seat and poppet concept. These development rigs included a 1” Seal Test Rig, a 3” Seal Test Rig, and a 3” Life Cycle Test Rig. Each of these activities demonstrated very low internal leakage performance. The seal test rigs improved internal leakage rates found on currently available aerospace valves by upwards of 3 orders of magnitude (< 0.5 SCIM) while subjected to relatively small actuator loads. The 3” Life Cycle Test Rig also demonstrated 5000 cycles of the test article with no detectable change in leakage rates.

In order to continue advancements to the self-aligning seat and poppet’s Technology Readiness Level (TRL), three test valves have been developed to demonstrate the potential application of this technology to various configurations, sizes, and environments (Fig. 4).

1) A 3” isolation valve for liquid flow (LN_2 and LH_2).
2) A 3” relief valve for gas flow (GHe chilled with LN_2 and LH_2).
3) An 8” pre-valve for gas and / or liquid flow (LN_2-chilled GHe and LH_2).

Fig. 4 Low Leakage Test Valves: LLIV (Left), LLRV (Center), LPV (Right)

III. Test Facility

Each of these test valves have undergone an initial test campaign conducted either with LN_2 or LN_2-chilled GHe (depending on application). This “LN_2 testing” was conducted at the Component Development Area (CDA), located at MSFC Building 4656 (Fig. 5, Fig. 6).

The CDA serves as a broadly utilized fluid components and systems test capability, as well as a place for ER14 engineers to assemble, test, and evaluate designs as they are developed. Once complete, this “LN_2 testing” will be followed up with “LH_2 testing” in the East Test Area at MSFC.

Fig. 5 MSFC Component Development Area (CDA)

Fig. 6 CDA Satellite View

IV. Low Leakage Isolation Valve (LLIV)

The Low Leakage Isolation Valve (LLIV) test article is a normally-open, bellows-actuated isolation valve with a 3-inch nominal seat diameter. The linear poppet design with pneumatic actuator allows seat stress to vary by changing actuator pressure. The hermetically-sealed bellows diameter and valve seat diameter are approximately equal to minimize the effect of inlet fluid pressure on seat force. The LLIV functions in a similar manner to a fill and drain valve, and is intended to demonstrate that the self-aligning seat and poppet technology will work in high-flow liquid environments (LN_2 and LH_2). (Fig. 7, Fig. 8).

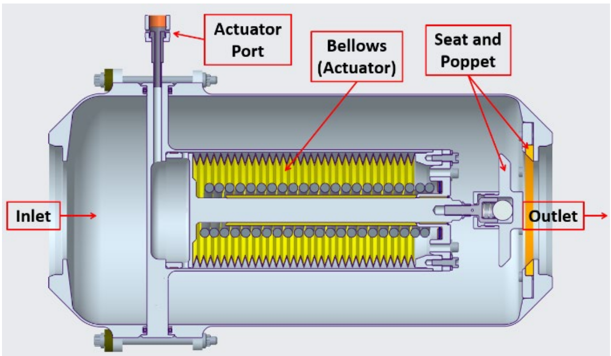

Fig. 7 Cross-Section of LLIV Model

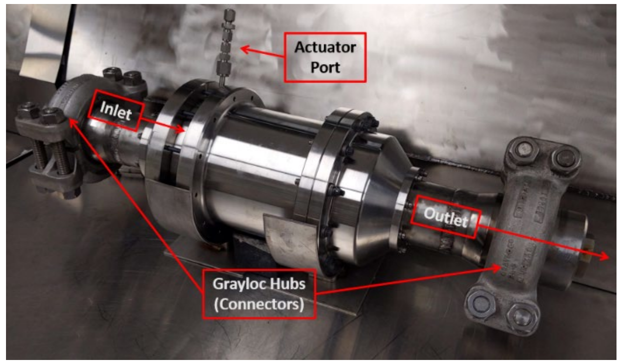

Fig. 8 Assembled LLIV Test Article

The LLIV is designed for operation down to liquid hydrogen temperatures and has a maximum design pressure of 115 psig for the test article, and 250 psig for the actuator. Additional LLIV design parameters are seen in Table 1.

Table 1: LLIV Design Parameters

Parameter	Value
Operating Temperature	-430 °F to +100 °F
Maximum Design Pressure (Valve)	115 psig
Maximum Expected Operating Pressure (Valve)	30 psig
Proof Pressure (Valve)	173 psig (1.5 x MDP) (only proofed to 55 psig)
Burst Pressure (Valve)	460 psig (4.0 x MDP)
Maximum Design Pressure (Actuator)	250 psig
Proof Pressure (Actuator)	375 psig (1.5 x MDP) (only proofed to 312 psig)
Burst Pressure (Actuator)	1000 psig (4.0 x MDP)
Media	GHe, GN_2, LN_2, GH_2, and LH_2
Flow Capacity	≤ 20 lbm/sec LH_2 (or 2,040 GPM LH_2)
Stroke Time	≤ 30 sec.
Internal Leakage (Goal)	≤ 1 SCIM Hydrogen @ -423 +/- 10 °F

The objectives of the Low Leakage Isolation Valve "LN_2 test" included:

1) Hydrostatically proof testing the LLIV to 55 psig.
2) Conducting cryogenic flow testing on the LLIV by flowing LN_2 though the valve at rates of 45, 90, 135, and 180 gallons per minute.
3) Determining the flow coefficient (C_v) of the LLIV during the flow test of the valve.
4) Conducting internal leak testing on the LLIV after the proof test, the water flow test, and after each cryogenic flow test.

The LLIV successfully completed the hydrostatic proof test at 55 psig, after which internal leakage rates were measured by submerging the TA in LN_2 until the temperature had equalized. After LN_2 surface bubbling had reached a minimum, the LLIV outlet was routed to a beaker of water, the valve inlet was pressurized with GHe, and the volume of gas entering the beaker was measured over a period of time.

During the initial internal leak test (prior to flow), a leakage rate of 6.5 SCIM was measured across the valve seat. The test article had been submerged in LN_2 for over 4 hours and LN2 surface bubbling had reached a minimum state, but actuator pressure was only set to 100 psig. Similar internal leakage rates were measured when actuator pressure was increased to 130 psig. The test article was cycled 5 times, and actuator pressure was increased again to 150 psig, where the leakage stopped. To verify these results, the actuator pressure was decreased to 145 psig (where internal leakage was observed once more), then increased again to 150 psig (at which point leakage rates returned to zero).

The LLIV was able to achieve the flow rates of 45, 90, 135, and 180 gallons per minute with average C_v values of 41.5, 61.5, 67.6, and 48.7 GPM / $psi^{1/2}$, respectively. When the LLIV was evaluated for internal leakage rates after high-volume LN_2 flow, it was discovered that the test article was now exhibiting extremely high internal leak rates, ranging from 116 to over 1700 SCIM. The valve was initially operating with actuator pressure set at 150 psig, but this value was increased after seeing progressively higher leak rates after the LN_2 flow test. Increasing the actuator pressure first to 185 psig, then to 200 psig provided results that were improved from 1700 SCIM, but still multiple orders of magnitude greater than desired leakage rates. See Table 2.

Table 2: LLIV Post-Flow Internal Leakage Rates

Flow Rate	Actuator Pressure	Inlet Pressure	Volume Displaced	Time	Leak Rate
45 GPM	155 psig	30 psig	750 mL	10.0 s	275 SCIM
90 GPM	155 psig	30 psig	1000 mL	5.0 s	732 SCIM
135 GPM	155 psig	30 psig	900 mL	2.5 s	1318 SCIM
180 GPM	155 psig	30 psig	950 mL	2.0 s	1739 SCIM
135 GPM	185 psig	30 psig	475 mL	15.0 s	116 SCIM
180 GPM	200 psig	30 psig	950 mL	4.0 s	870 SCIM

During subsequent inspections of the test article, it was discovered that the valve seat had multiple scratches and pits, with material from the seat sticking to the poppet (see figure 9A and 9B). This damage was likely caused by Foreign Object Debris (FOD) present in the LN_2 supply tank. It was also discovered that the poppet spring (see figure 9C) was significantly less stiff than what was required (with a rate of only 12 lbf/in, instead of 52 lbf/in). The LLIV is currently undergoing a follow-on test (see Figure 9D) to verify that leakage is occurring between the contacting surfaces of the poppet and seat (and not past the knife edge on the underside of the seat), as seen in figure 9E.

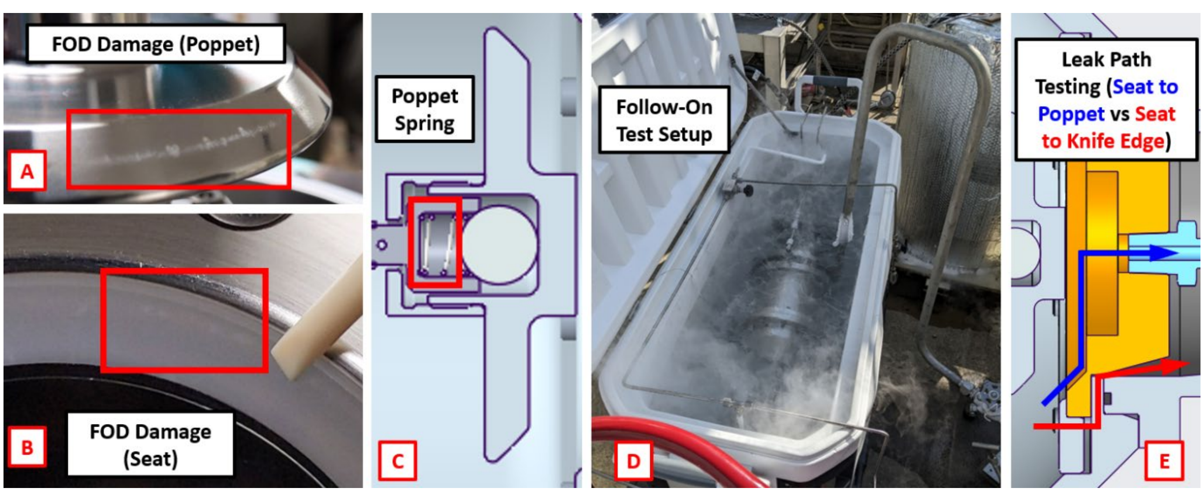

Fig. 9A through 9E

V. Low Leakage Relief Valve (LLRV)

The Low Leakage Relief Valve (LLRV) test article is a normally-closed, piloted relief valve with a 3-inch nominal seat diameter. The LLRV is intended to demonstrate that the self-aligning seat and poppet technology will function in a wide range of flow rates for cryogenic gas systems (GHe chilled with LN_2 and LH_2) As seen in Figure 10, the valve is configured in a right angle (inlet to outlet), with the pilot valve externally mounted above and connected to the outlet bore.

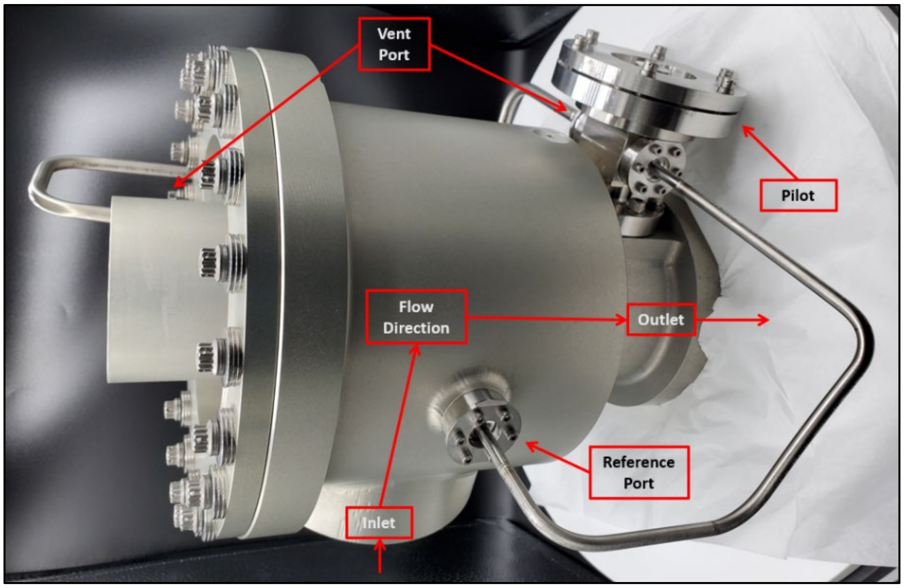

Fig. 10 Low Leakage Relief Valve (LLRV) Configuration

The LLRV is designed for operation down to liquid hydrogen temperatures and has a maximum design pressure of 115 psig. Cracking pressure of the pilot valve was designed to fall between 17 and 20 psid, with full flow pressure reaching a maximum of 25 psid. Additional design parameters for the LLRV are seen in Table 3.

Table 3: LLRV Design Parameters

Parameter	Value
Minimum Reseat Pressure	17 psid
Maximum Cracking Pressure	20 psid
Maximum Full Flow Pressure	25 psid
Operating Temperature	-423 °F to +170 °F
Maximum Design Pressure	115 psig
Proof Pressure	173 psig (1.5 x MDP)
Burst Pressure	460 psig (4.0 x MDP)
Media	GHe, GN_2
Flow Capacity	$3.0\ in^2 \leq C_d \cdot A \leq 4.0\ in^2$
Response Time	≤ 1 sec.
Internal Leakage (Goal)	≤ 1 SCIM Hydrogen @ -423 +/- 10 °F

Although mounted to the outlet of the main valve body, the pilot valve is also connected to the inlet bore via the reference port (Fig. 11), as well as the vent cavity via the vent port. The inlet bore and vent cavity (Fig. 12) are connected via a small orifice (or "bleed hole"), which allows the test article to return to its normally-closed state after actuation. As inlet pressure reaches pilot valve cracking pressure, the pilot opens and the vent cavity depressurizes.

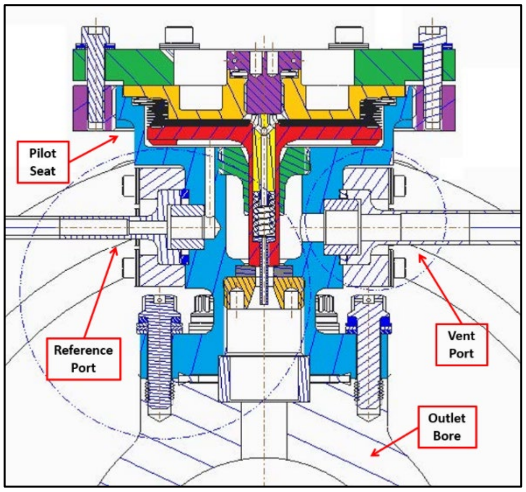

Fig. 11 LLRV Pilot Valve Cross-Section

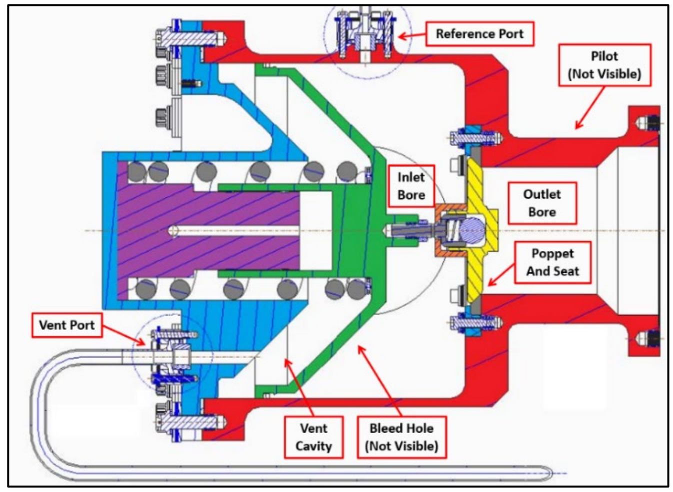

Fig. 12 LLRV Main Valve Cross-Section

Once the pressure differential between the inlet bore and the vent cavity reaches the appropriate level, the main spring preload is overcome, and the main valve begins to open (Fig. 13). This allows direct connection between inlet and outlet, thus relieving inlet pressure. As inlet pressure drops below the pilot valve reseat pressure, the pilot valve closes and allows pressure to build in the vent cavity via the bleed hole. As pressure in the vent cavity and inlet bore begins to equalize, the force of the pressure differential is overcome by the main spring preload, which returns the test article to its normally-closed state.

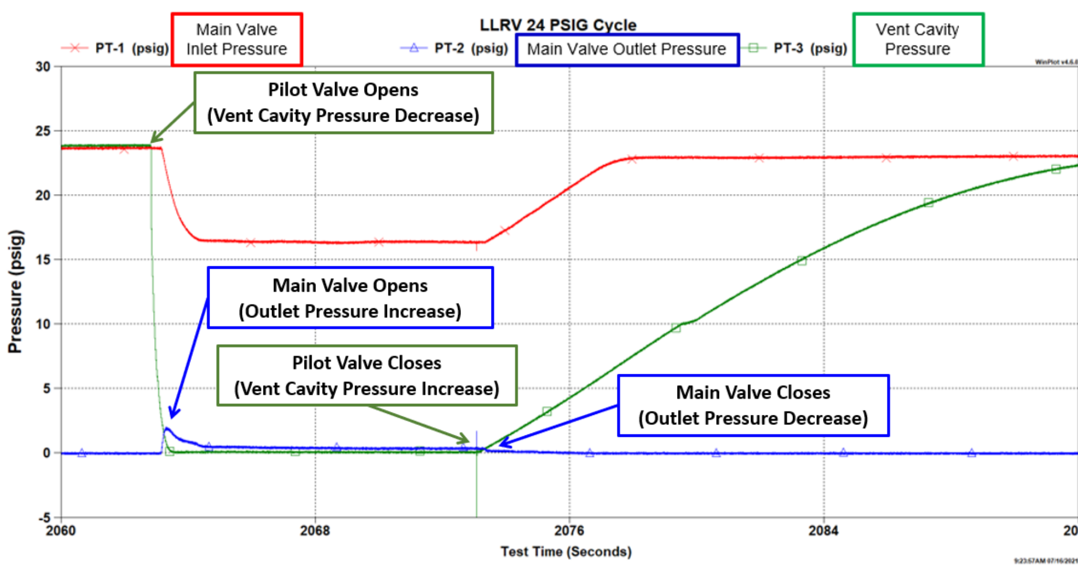

Fig. 13 Pressure Levels During an LLRV Cycle

The objectives of the Low Leakage Relief Valve “LN_2 test” included:

1) Proof testing the LLRV to 144 psig.
2) Conducting an external leakage check on the LLRV.
3) Cycling the LLRV at ambient and cryogenic conditions
4) Measuring internal leakage rates of the LLRV at various points of the test program (after proof test, after ambient cycles, after cryogenic chill-in, and after cryogenic cycles).
5) Determining flow performance (crack and reseat pressures) of the LLRV.

The LLRV successfully completed the proof test at 144 psig, after which point an external leakage check was conducted. The LLRV was pressurized to 50 psig and a leak check (soap) solution was utilized to monitor for any signs of external leakage (bubbles) at interfaces between the pilot and main valve, end cap, and sense tubes. Internal leakage rate testing was conducted by connecting flexible PVC tubing (“Tygon”) to the outlet of the test article. The end of the Tygon tubing was submerged in water and observed for a minimum of 2 minutes, capturing any bubbles within an inverted graduated cylinder (as shown in Fig. 14). If no bubbles were observed, the Tygon tubing would be exchanged out for a flowmeter, which would be observed until the reading stabilized. Unlike the LLIV and the LPV, submerging the LLIV in LN_2 to achieve cryogenic temperatures was not feasible due to the nature of the valve (relief valve). A spraybar for LN_2 was instead placed above the test article (Fig. 15) in order to chill in the valve body.

Fig. 14 Bubble Check

Fig. 15 LLRV with Spraybar

Flow performance (crack and reseat pressures) of the LLRV was very consistent. Average results for ambient and cryogenic conditions are summarized in Table 4:

Table 4: LLRV Flow Performance (Average Values)

Condition	Fluid Temp. (°F)	Body Temp. (°F)	Cracking Pressure (psig)	Cracking Std. Dev.	Reseat Pressure (psig)	Reseat Std. Dev.
Ambient	51.4	53.5	19.8	0.2	19.8	0.2
Cryogenic	-173.7	-240.3	20.8	0.9	20.2	0.6

Internal leakage results for the LLRV were excellent, with no bubbles observed during any of the measurement periods. Exchanging the Tygon tubing out for a flowmeter revealed ambient internal leakage rates of 0.060 Standard Cubic Centimeters per Second (SCCM) or less. This is roughly equivalent to 0.004 SCIM, and is well below the desired leakage rates for this activity. Cryogenic leakage rates were too low to measure with the flowmeter, not exceeding the cold cavity pressure drop (or "cryopumping") created within the outlet tubes exposed to cryogenic fluid. These results are shown in Table 5:

Table 5: LLRV Internal Leakage Rates

Condition	Cycles (Total)	Bubbles Observed?	Flowmeter Reading (SCCM)	Notes
Ambient	30	No	0.045	-
Ambient	45	No	0.060	-
Cryogenic	45	No	N/A	Leak Rate ≤ Cryopumping
Cryogenic	60	No	N/A	Leak Rate ≤ Cryopumping

VI. Large Pre-Valve (LPV)

The Large Pre-Valve (LPV) test article is a normally-closed, "fueldraulic" isolation valve with an 8-inch nominal seat diameter. It is generally expected that larger valves will have more difficulty in obtaining low leakage rates due to an increased seat area. Understanding and overcoming design challenges for large valves is important to enabling in-space long term cryogenic storage for high-flow applications. The LPV is intended to provide insight into the abilities to scale the self-aligning seat and poppet design to large main propulsion system pre-valves (similar to what may be required on vehicles for long duration missions).

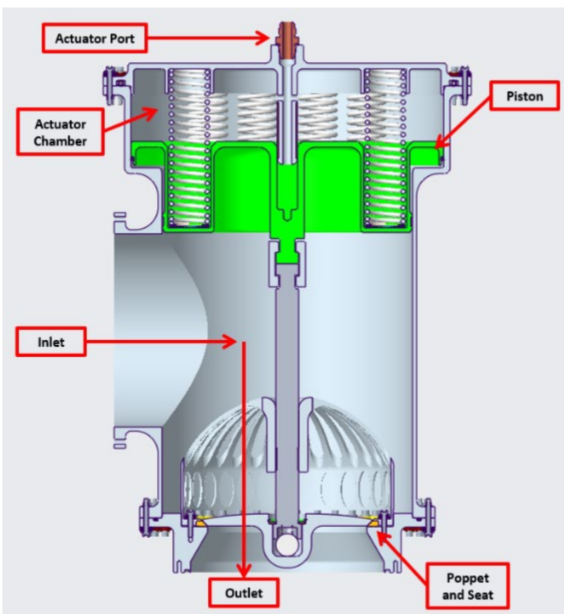

Fig. 16 Cross-Section of LPV Model

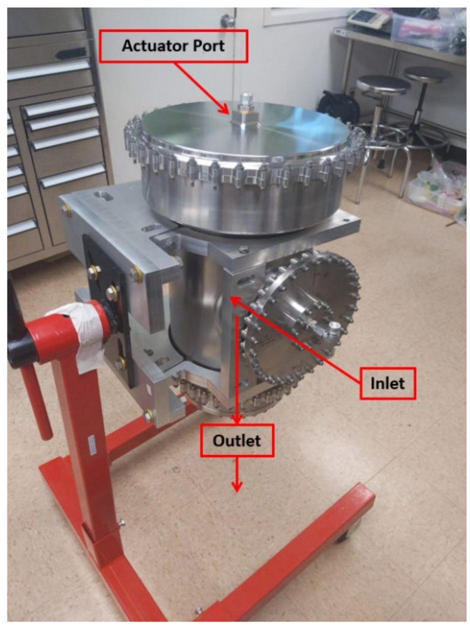

Fig. 17 LPV in Assembly Stand

The LPV test article is configured in a right angle (inlet to outlet), with the actuator port located at the top of the valve (Fig. 16, Fig. 17). The test article utilizes a pair of solenoid valves (not shown in images) as Special Test Equipment (STE) to fill or vent the actuator. One of these solenoid valves is installed upstream of the actuator port, the other is installed downstream of the port. In its normal (non-energized state), the LPV has 10 compression springs exerting approximately 1,250 lbf (total) against the piston, which translates through a coupling shaft to keep the self-aligning poppet and seat in contact.

The LPV is designed for operation down to liquid hydrogen temperatures and has a maximum design pressure of 30 psig, with a maximum pressure drop of 5 psid across the valve. Additional design parameters for the LPV are shown in Table 6.

Table 6: LPV Design Parameters

Parameter	Value
Operating Temperature	-430 °F to +100 °F
Maximum Design Pressure	30 psig
Proof Pressure	45 psig (1.5 x MDP)
Burst Pressure	120 psig (4.0 x MDP)
Media	GHe, GN_2, LN_2, GH_2, and LH_2
Pressure Drop	<5 psid
Stroke Time	≤ 60 seconds
Internal Leakage (Goal)	≤ 1 SCIM Hydrogen @ -423 +/- 10 °F

The LPV remains in a closed position while the pressure differential between the inlet chamber and the actuator chamber does not exceed approximately 19 psid (Fig. 18). Energizing the solenoid valves will vent the actuator chamber (**Event A**), causing the pressure differential to approach 25 psid. This pressure differential overcomes the 1,250 lbf preload of the compression springs and pushes the piston into the actuator chamber, which opens the test article (**Event B**).

To close the LPV, the solenoid valves are de-energized, repressurizing the actuator chamber (**Event C**). This reduction in the pressure differential allows the compression spring preload to return the test article to its normally closed position (**Event D**).

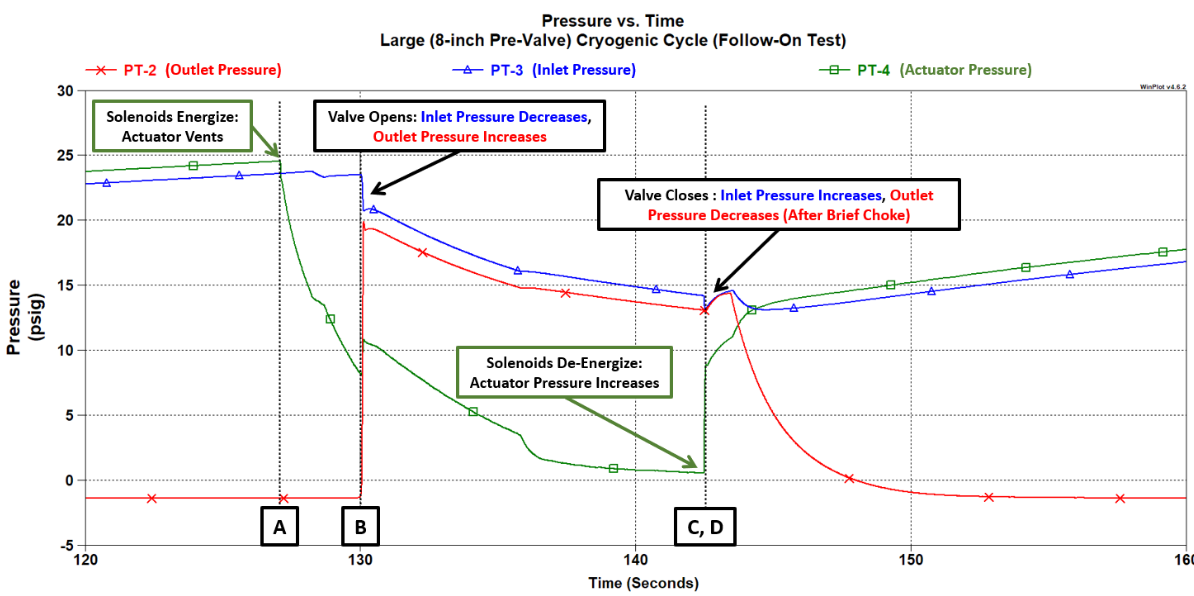

Fig. 18 Pressure Levels During an LPV Cycle

The objectives of the Large Pre-Valve "LN_2 test" included:

1) Proof testing the LPV to 45 psig.
2) Conducting an external leakage check on the LPV.
3) Cycling the LPV at ambient and cryogenic conditions
4) Measuring internal leakage rates of the LPV at various points of the test program (after proof test, after ambient cycles, after cryogenic chill-in, after cryogenic cycles, and after a return to ambient temperatures).

The LPV successfully completed the proof test at 45 psig, after which point an external leakage check was conducted. The LPV was pressurized to 25 psig and a leak check (soap) solution was utilized to monitor for any signs of external leakage (bubbles) at exposed fittings and other connection points. Not all fittings were accessible due to the size of the test article and its location within a tank (Fig. 19), so a pressure decay check was performed as well, monitoring for any pressure drop over the course of 10 minutes.

Fig. 19 LPV in Test Setup

Fig. 20 Split Configuration for Flowmeter

Internal leakage rate testing was conducted by connecting Tygon tubing to the outlet of the test article, submerging the end of the tubing in water, and capturing any bubbles within an inverted graduated cylinder over the course of 2 minutes (minimum). For measurements where a lower internal leakage rate was observed, this time period was extended to 5 minutes. The Tygon tubing would then be exchanged with a flowmeter and another measurement would be performed (Fig. 20).

During initial testing, the LPV demonstrated internal leakage rates that, although much lower than similarly-sized valves, were higher than expected (Table 7).

Table 7: Initial LPV Internal Leakage Rates

Cumulative Cycles	Temperature Condition	Bubble Leak Rate			Flowmeter
		ML	Time (s)	SCIM	SCIM
0	Ambient	0	300	0	0.07
6	Ambient	300	300	3.66	3.36
25	Cryogenic	310	300	3.78	3.66
50	Cryogenic	150	120	4.58	4.03
75	Cryogenic	160	120	4.88	4.03
100	Cryogenic	150	120	4.58	4.15
100	Ambient	0	300	0	0.05
105	Ambient	0	300	0	0.08

Initial testing also revealed that a significant pinging sound would emanate from the test article whenever it was cycled at cryogenic temperatures, and that significant leakage was occurring between the actuator chamber and the inlet. Post-test inspection revealed that the compression springs had been misaligned with the opposing wells that each spring end sits within. This misalignment caused the springs to bend and twist during actuation, causing significant lateral force on the piston, and accounting for both the pinging sound observed, and the leakage between the actuator chamber and inlet.

After the misalignment had been identified, the LPV was re-assembled with new tooling to prevent actuator misalignment from occurring. The LPV was then re-tested under a shorter, "Follow-On" test series to confirm that the issues observed during initial testing had been corrected. These changes not only improved actuator performance (reducing piston seal leakage and eliminating the pinging noises), but also made a significant improvement to leakage rates observed at cryogenic temperatures (Table 8).

Table 8: LPV Follow-On Testing Internal Leakage Rates

Cumulative Cycles	Temperature Condition	Bubble Leak Rate			Flowmeter
		ML	Time (s)	SCIM	SCIM
105	Ambient	0	120	0	0.04
110	Ambient	0	120	0	0.07
112	Cryogenic	62	120	1.89	1.28
120	Cryogenic	64	120	1.95	1.14
120	Ambient	0	120	0	0.04
125	Ambient	0	120	0	0.04

VII. Conclusion

There are significant challenges that exist for future long duration missions that seek to utilize cryogenic propellants. Valve technology that is currently available could allow for unacceptable amounts of propellant loss. The self-aligning seat and poppet design could help mitigate the risk of propellant loss due to internal leakage. The test valves utilizing this technology have shown good results so far, but will continue to be evaluated over the course of LH_2 in 2023. A successful test campaign will likely result in a search for an industry partner to help develop a low leakage valve that further advance this technology towards flight hardware.

Acknowledgments

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