Advancements in Low Leakage Valves for Long Duration Missions.

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This paper reports on the advancements in the development of low-leakage valve technology for cryogenic environments, 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 test 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.
GHe = 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.

II. Introduction

Current aerospace cryogenic valve technology presents challenges to potential long duration missions that utilize cryogenic propellants. One such challenge is internal leakage, which occurs when a valve's sealing surfaces fail to create a tight seal, allowing propellant to continue to flow through the system. This challenge is particularly pronounced in the case of cryogenic fluids, such as hydrogen. Cryogenic fluids have relatively small molecule sizes, which means that they can more easily permeate through materials than the larger molecules found in warmer propellants.

Cryogenic propellants are commonly used on launch vehicles, which only need to store these propellants for a few minutes. Many mission payloads (such as small interplanetary or long-life communication satellites) achieve very low internal leakage rates by employing hypergolic propellants in combination with relatively small valves. Hypergolic propellants have higher operating temperatures and viscosities (which minimizes the risk of internal leakage), but lack the efficiency that will likely be required for future long-duration missions. Larger vehicles for these missions are expected to utilize cryogenic-based chemical and nuclear systems to achieve mission requirements. Some early propulsion concepts have projected a need for valves with a nominal size ranging from 3-inches to 10-inches.

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The cryogenic aerospace valves that are currently available will frequently prioritize other design parameters such as physical footprint, simplicity, and low mass. This makes butterfly valves a popular choice on launch vehicles with high flow rates, but they also have a drawback of high internal leakage rates. These leakage rates can range from 100 to 300 Standard Cubic Inches per Minute (SCIM) for 3-inch valves, or upwards of 2,000 SCIM for 10-inch 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

One type of valve that is commonly used in applications where low internal leakage rates are critical is the poppet valve. Poppet valves are designed with a disc-shaped sealing element that closes against a seat to stop the flow of fluid or gas. The sealing element is often made from a flexible material such as rubber or elastomer, which allows it to conform to the valve seat and create a tight seal. The disc can be moved by various means such as a spring, a solenoid, or a pneumatic actuator. Some advantages of poppet valves include a reduced amount of sealing surface wear, and the ability to provide a consistent sealing stress across the sealing surface. This consistent sealing stress can help achieve a tight seal, which can minimize the risk of internal leakage.

In a poppet valve, the poppet and valve seat must make contact to create a tight seal and prevent fluid from leaking through. If the surfaces of the valve seat or poppet are rough, or have irregular wavy shapes (even on a microscopic level), it can result in poor contact, and allow fluid to leak through these gaps. Additionally, if the valve seat and poppet are not properly aligned, do not have tight tolerances, or have imperfections in the concentricity (as shown in Fig. 2), it can result in poor contact between the poppet and seat, which can lead to internal leakage.

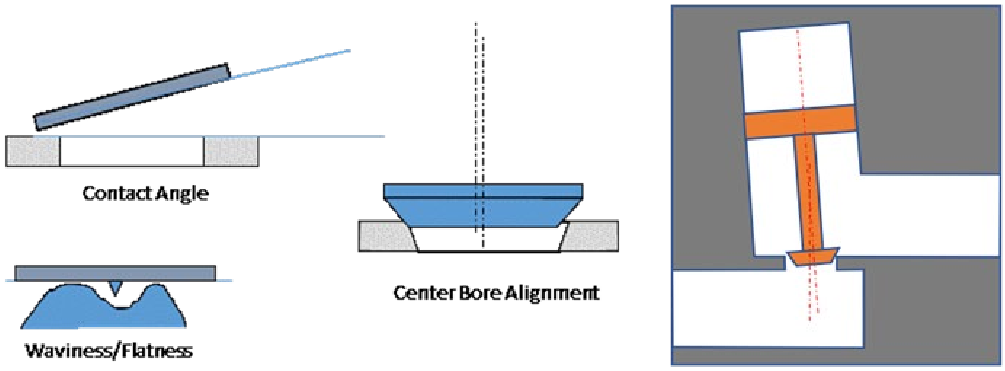


Fig. 2 Imperfections and Misalignments Between Sealing Surfaces

Due to these common limitations, a design has been proposed that can reduce or eliminate some of the causes of internal leakage in poppet valves. This paper presents the findings of a test program designed to assess the performance of low-leakage cryogenic valves by evaluating their performance within a variety of environments and applications.

III. Background

The Valves, Actuators & Ducts Design and Development Branch (ER14) at Marshall Space Flight Center (MSFC) has created a self-aligning poppet and seat design (shown in Fig. 3) which allows a valve to be more tolerant of imperfect contact. This design utilizes a metallic poppet head with five degrees of freedom (as depicted in Fig. 4), allowing the poppet to self-align with the seat, reducing the need for tight tolerances. A spherical poppet and conical seat is a relatively conventional 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 [1].

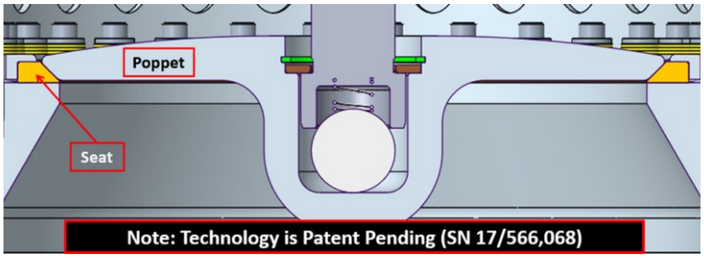


Fig. 3 Self-Aligning Poppet and Seat Design

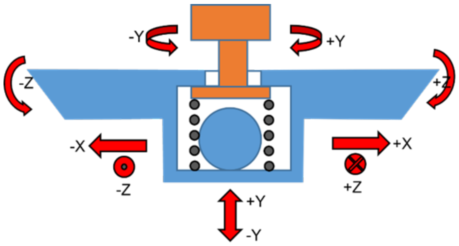


Fig. 4 Degrees of Freedom

ER14 has 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-inch Seal Test Rig, a 3-inch Seal Test Rig, and a 3-inch 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-inch Life Cycle Test Rig also demonstrated over 500 cycles of the test article with no detectable change in leakage rates [2].

To continue advancing the self-aligning seat and poppet's Technology Readiness Level (TRL), three test valves have been developed to demonstrate the application of this technology to various configurations, sizes, and environments (shown in Fig. 5).

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. 5 Low-Leakage Test Valves: LLIV (Left), LLRV (Center), LPV (Right)

IV. Test Facilities

Each of these test valves underwent 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 (shown in 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.

Upon the completion of LN_2 testing, the test articles were moved to Test Stand 300 (situated in the East Test Area at MSFC), to undertake LH_2 testing (test bunker shown in Fig. 7).

Fig. 6 Component Development Area (CDA)

Fig. 7 Test Stand 300 Bunker

V. Low Leakage Relief Valve (3-Inch)

A. Test Article Description

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 Fig. 8, the valve is configured in a right angle (inlet to outlet), with the pilot valve externally mounted above and connected to the outlet bore.

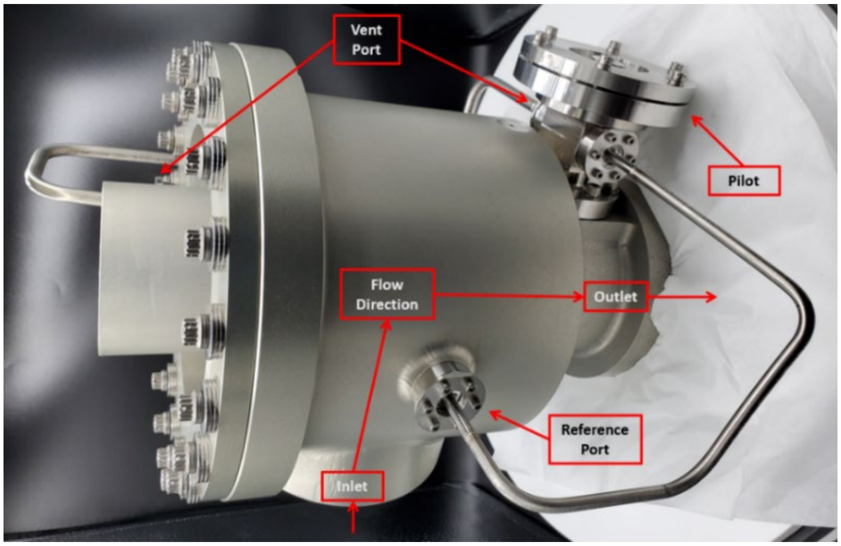


Fig. 8: Low-Leakage Relief Valve (LLRV)

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 shown in Table 1.

Table 1: 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, GH_2
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 (as shown in Fig. 9), as well as the vent cavity via the vent port. The inlet bore and vent cavity (as shown in Fig. 10**)** 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.

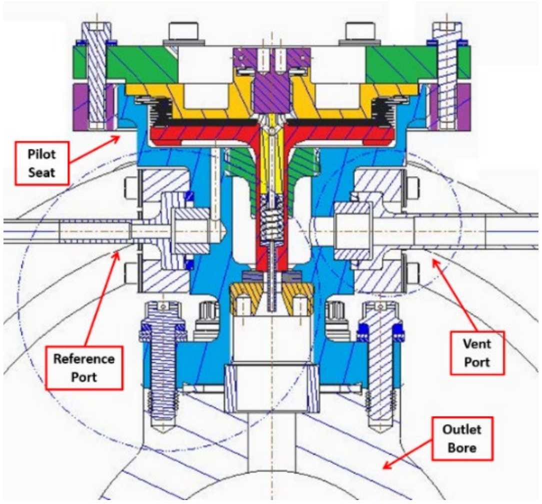


Fig. 9: LLRV Pilot Cross-Section

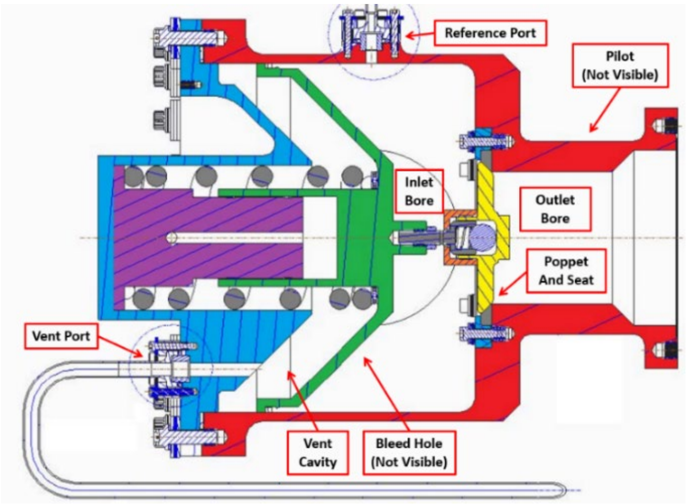


Fig. 10: LLRV Cross-Section

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. 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. 11 illustrates the different pressure levels over time for the test article.

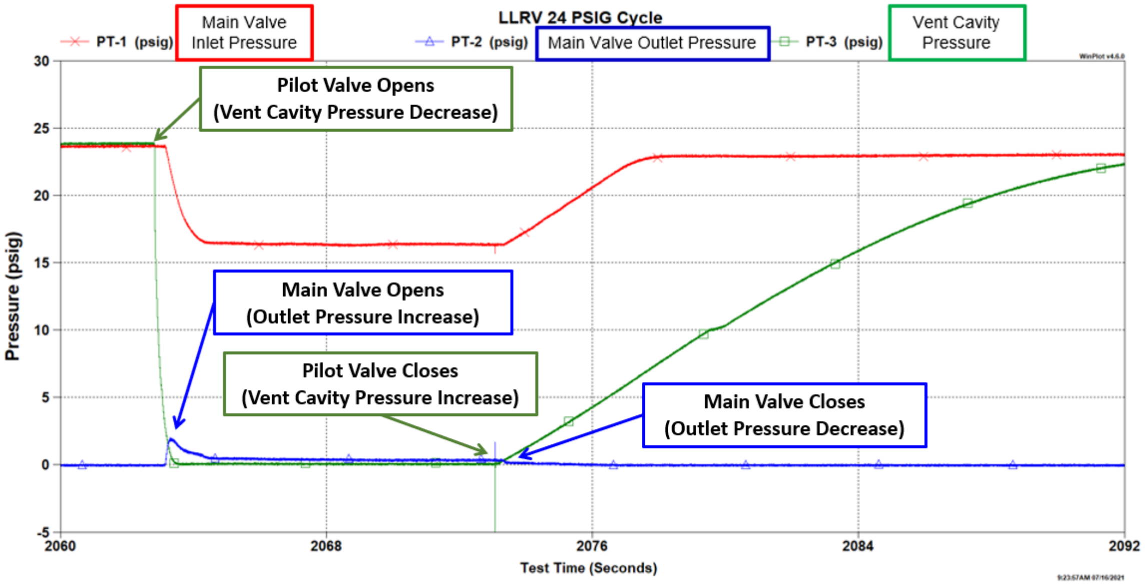


Fig. 11: Pressure Levels During an LLRV Cycle

B. LLRV LN_2 Test Series

The objectives of the "LN_2 test" for the LLRV 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, followed by an external leak check. The LLRV was pressurized to 50 psig and a soap solution was used to monitor for any signs of external leakage at various interfaces. Internal leakage 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. 12). 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 LLRV 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 (as shown in Fig. 13) in order to chill-in the valve body.

Fig. 12: Bubble Check

Fig. 13: CDA Spraybar Setup

Flow performance (crack and reseat pressures) of the LLRV was very consistent. Average results for ambient and cryogenic conditions are summarized in Table 2:

Table 2: LLRV Flow Performance (Average Values)

Condition	Fluid Temp (°F)	Body Temp (°F)	Cracking (psig)	Reseat (psig)
Ambient	51.4	53.5	19.8	19.8
Cryogenic	-173.7	-240.3	20.8	20.2

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 3:

Table 3: 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

C. LLRV “LH_2” Test Series Overview

After completing “LN_2 testing”, the LLRV was moved to Test Stand 300 to conduct “LH_2 testing”. Since the test article functions as a relief valve, cryogenic hydrogen gas (GH_2) was used as the fluid medium instead of LH_2. The primary objective of the “LH_2 test” for the LLRV was to measure the internal leakage rate through the valve after subjecting the test article flow of GH_2. As with the testing conducted at the CDA, an LN_2 spraybar was placed above the test article in order to chill-in the valve body. The LLRV is shown in its test setup in Fig. 14 and Fig. 15.

Fig. 14: LLRV Prior to LH_2 Test

Fig. 15: LLRV Post LH_2 Test

To prevent air and moisture from entering the system (also known as “cryopumping”) and impacting the operation of the LLRV, a check valve (rated for 5 psig cracking pressure) was installed downstream of the flow meters. Although this check valve was not included on the original schematic, its approximate location has been noted in Fig. 16. Color-coded boxes have also been included, which correspond to the parameters plotted in subsequent figures.

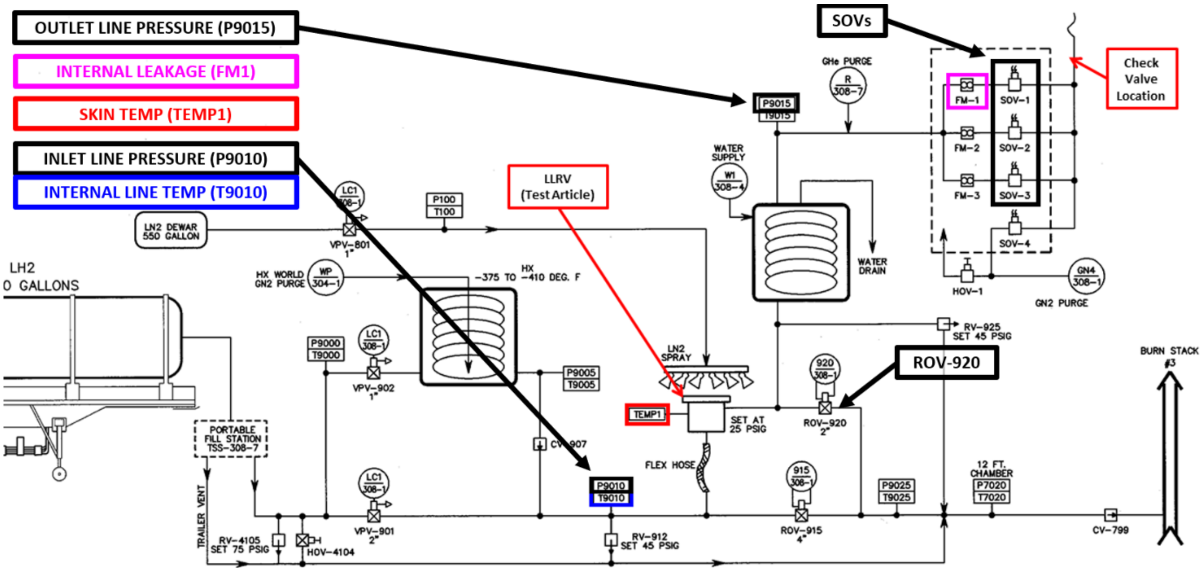


Fig. 16: LLRV “LH_2” Test Schematic Details

A total of five “flow and leak tests” were performed on the LLRV. During each period of hydrogen flow, the LLRV was allowed to cycle (open and close), while ROV-920 remained open, and SOV-1, SOV-2, and SOV-3 were closed. This configuration directed the hydrogen from the test article to the burn stack. Once the test article was closed, a leak measurement was taken by closing ROV-920 and opening the SOVs as required. This would allow hydrogen to flow through the flowmeter preceding each SOV. Although it was planned to open the SOVs in descending order (as shown in Table 4), the leakage rates observed during the tests did not exceed the thresholds that would require the use of FM-2 and FM-3. Therefore, only data from FM-1 has been included in the report.

Table 4: LLRV "LH_2" Test Flow Meters

Flow Meter	Solenoid	Range (SCIM)	Part Number
FM-3	SOV-3	60 – 30,500	HFM-D-301A (0-500 SLPM)
FM-2	SOV-2	0.6 – 305	HFM-D-300A (0-5 SLPM)
FM-1	SOV-1	1.2 – 61	GM50A (0-1000 SCCM)

Due to the check valve placed to prevent cryopumping, a build-up of outlet line pressure between the test article and the flowmeters could potentially occur if ROV-920 was closed before the test article outlet line had been fully drained of hydrogen. This "short drain" could potentially lead to a large initial reading of internal leakage (as was later seen in testing for the LLIV and LPV), but was done in order to retain cryogenic temperatures for as long as possible. Although the check valve allowed a build-up of outlet line pressure between the test article and the flowmeters to occur, this value never exceeded 5 psig for the LLRV. As such, the large leakage rates associated with these pressures from the later tests conducted on the LLIV and LPV were not observed for the LLRV. This may be due to a combination of factors, such as a lower "true" leakage rate from the relief valve itself, a shorter duration of measurement, and the exposure of Special Test Equipment (STE) to the LN_2 spray bar.

A general plot of the LLRV LH_2 Test timeline and parameters measured is shown in Fig. 17. Internal leakage rates measured for the LLRV were again excellent, consistently falling under 1.0 SCIM. A more detailed look at individual LH_2 Leak Tests for the LLRV is included on subsequent pages.

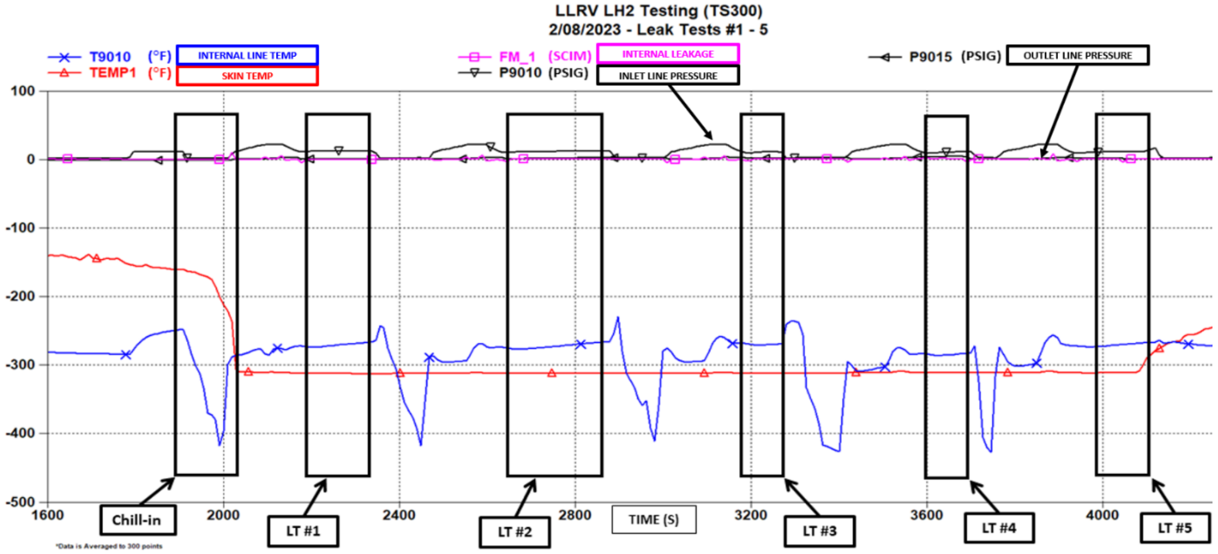


Fig. 17: Overview of LLRV "LH_2" Test Data

D. LLRV “LH_2” Flow and Leak Test #1

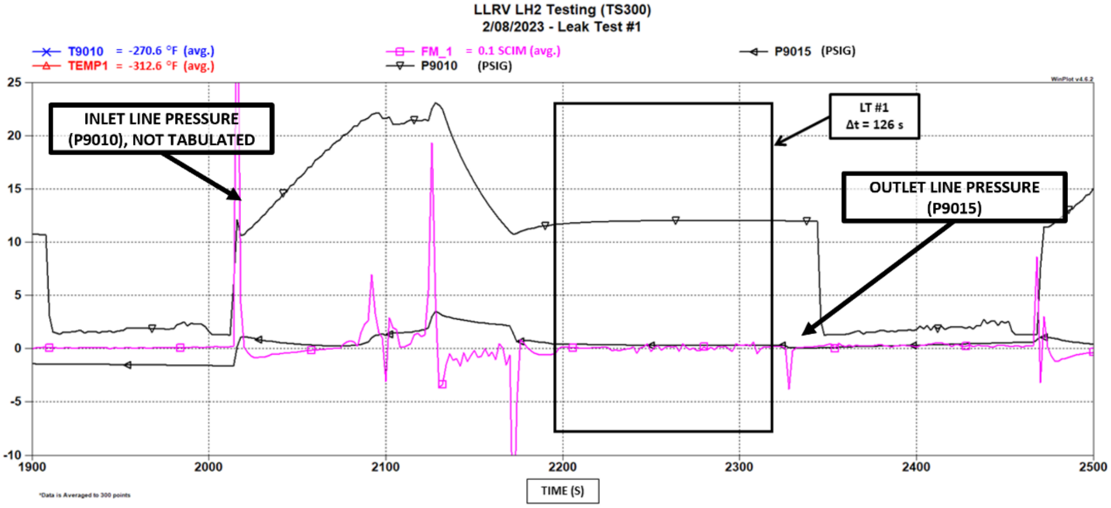


Fig. 18: LLRV Flow and Leak Test #1

For LLRV Leak Test and Measurement #1, values were recorded over a duration of approximately 126 seconds, as shown in Fig. 18. Internal line temperature (T9010) rises at a slow rate due to the LN_2 spray bar, and the test article skin temperature (TEMP1) is held constant. Outlet line pressure (P9015) stays relatively stable throughout the measurement staying at or below 0.4 psig. Internal leakage was recorded at rates of 0.5 SCIM or less. It should be noted that although inlet line pressure is shown in the figure, it is not tabulated below.

Table 5: LLRV “LH_2” Leak Measurement #1 (2200s)

	INTERNAL LINE TEMP	TA SKIN TEMP	INTERNAL LEAKAGE	OUTLET LINE PRESSURE
Time (s)	T9010 (°F)	TEMP1 (°F)	FM1 (SCIM)	P9015 (psig)
2200	-274.2	-312.6	0.2	0.40
2210	-273.9	-312.5	0.2	0.39
2220	-273.2	-312.5	0.0	0.36
2230	-272.7	-312.8	-0.2	0.33
2240	-271.9	-312.5	0.2	0.31
2250	-271.2	-312.4	-0.2	0.30
2260	-270.7	-312.4	0.5	0.30
2270	-270.1	-312.3	-0.2	0.30
2280	-269.4	-312.3	-1.0	0.27
2290	-268.9	-312.9	0.0	0.28
2300	-268.2	-312.9	-0.2	0.27
2310	-267.7	-313.0	-0.1	0.29
2320	-267.3	-313.2	0.0	0.30

E. LLRV "LH_2" Flow and Leak Test #2

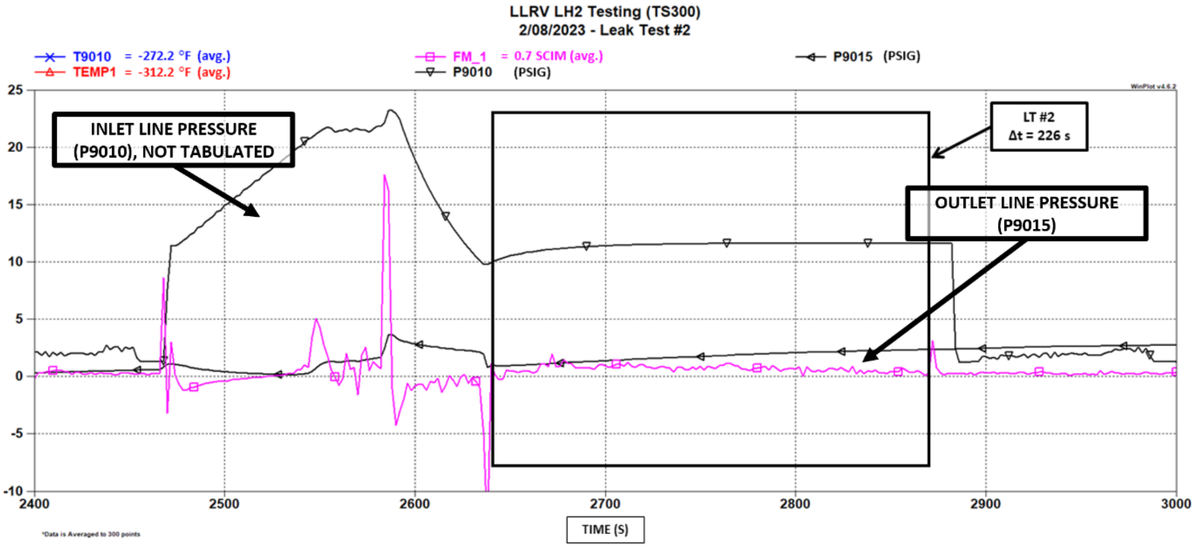
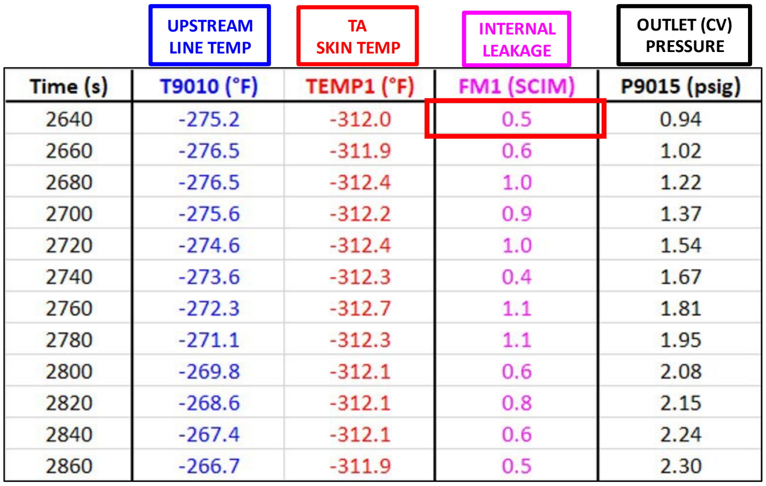


Fig. 19: LLRV Flow and Leak Test #2

For LLRV Leak Test and Measurement #2, values were recorded over a duration of approximately 226 seconds, as shown in Fig. 19. Internal line temperature (T9010) rises at a slow rate due to the LN_2 spray bar, and the test article skin temperature (TEMP1) is held constant. Over the course of the measurement, outlet line pressure (P9015) increases from a value of 0.94 psig to 2.30 psig, but still stays well below the 5 psig cracking pressure of the check valve. Internal leakage was recorded at rates ranging from 0.4 SCIM to 1.1 SCIM. Although the effects from outlet line pressure on the check valve are believed to be minimal or non-existent, a larger backpressure can also result in higher internal leakage rates due to a smaller net sealing force acting across the poppet and the seat. As such, it is believed that the most accurate value for internal leakage is found at the local minimum for outlet pressure and the active flowmeter. In the case of LLRV Leak Measurement #2, this value was 0.5 SCIM, occurring at a time value of approximately 2640s. It should be noted that although inlet line pressure is shown in the figure, it is not tabulated below.

Table 6: LLRV "LH_2" Leak Measurement #2 (2640s)



	UPSTREAM LINE TEMP	TA SKIN TEMP	INTERNAL LEAKAGE	OUTLET (CV) PRESSURE
Time (s)	T9010 (°F)	TEMP1 (°F)	FM1 (SCIM)	P9015 (psig)
2640	-275.2	-312.0	0.5	0.94
2660	-276.5	-311.9	0.6	1.02
2680	-276.5	-312.4	1.0	1.22
2700	-275.6	-312.2	0.9	1.37
2720	-274.6	-312.4	1.0	1.54
2740	-273.6	-312.3	0.4	1.67
2760	-272.3	-312.7	1.1	1.81
2780	-271.1	-312.3	1.1	1.95
2800	-269.8	-312.1	0.6	2.08
2820	-268.6	-312.1	0.8	2.15
2840	-267.4	-312.1	0.6	2.24
2860	-266.7	-311.9	0.5	2.30

F. LLRV “LH_2” Flow and Leak Test #3

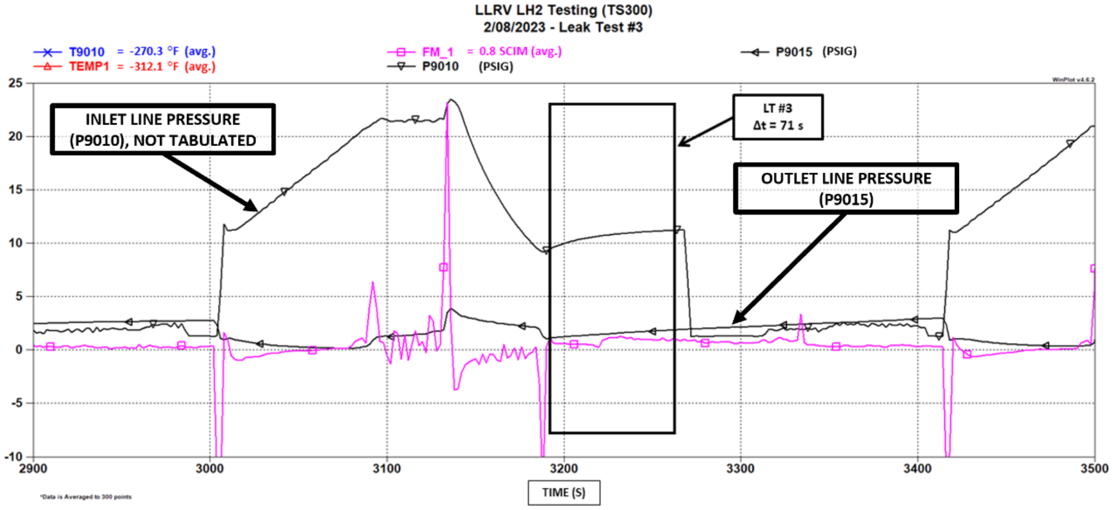
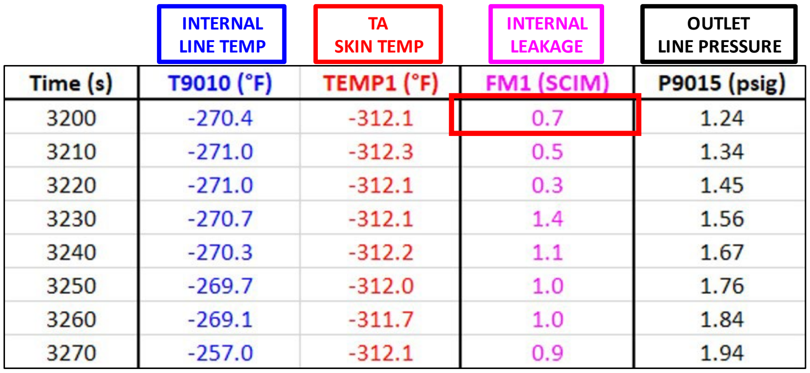


Fig. 20: LLRV Flow and Leak Test #3

For LLRV Leak Test and Measurement #3, values were recorded over a duration of approximately 71 seconds, as shown in Fig. 20. Internal line temperature (T9010) rises at a slow rate due to the LN_2 spray bar, and the test article skin temperature (TEMP1) is held constant. Over the course of the measurement, outlet line pressure (P9015) increases from a value of 1.24 psig to 1.94 psig, but still stays well below the 5 psig cracking pressure of the check valve. Internal leakage was recorded at rates ranging from 0.3 SCIM to 1.4 SCIM. Although the effects from outlet line pressure on the check valve are believed to be minimal or non-existent, a larger backpressure can also result in higher internal leakage rates due to a smaller net sealing force acting across the poppet and the seat. As such, it is believed that the most accurate value for internal leakage is found at the local minimum for outlet pressure and the active flowmeter. In the case of LLRV Leak Measurement #3, this value was 0.7 SCIM, occurring at a time value of approximately 3200s. It should be noted that although inlet line pressure is shown in the figure, it is not tabulated below.

Table 7: LLRV “LH_2” Leak Measurement #3 (3200s)



	INTERNAL LINE TEMP	TA SKIN TEMP	INTERNAL LEAKAGE	OUTLET LINE PRESSURE
Time (s)	T9010 (°F)	TEMP1 (°F)	FM1 (SCIM)	P9015 (psig)
3200	-270.4	-312.1	0.7	1.24
3210	-271.0	-312.3	0.5	1.34
3220	-271.0	-312.1	0.3	1.45
3230	-270.7	-312.1	1.4	1.56
3240	-270.3	-312.2	1.1	1.67
3250	-269.7	-312.0	1.0	1.76
3260	-269.1	-311.7	1.0	1.84
3270	-257.0	-312.1	0.9	1.94

G. LLRV “LH_2” Flow and Leak Test #4

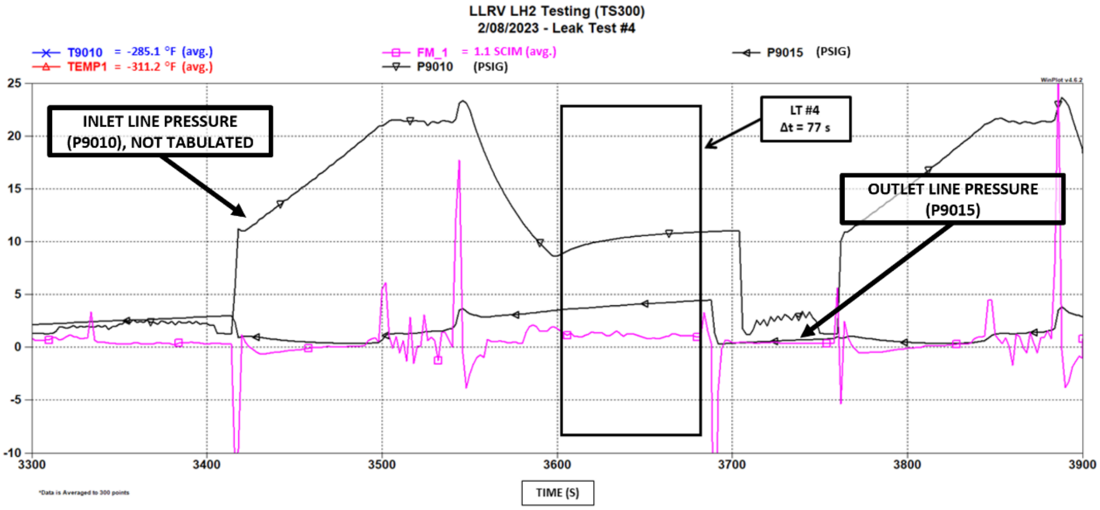


Fig. 21: LLRV Flow and Leak Test #4

For LLRV Leak Test and Measurement #4, values were recorded over a duration of approximately 77 seconds, as shown in Fig. 21. Internal line temperature (T9010) and test article skin temperature (TEMP1) are held constant due to the LN_2 spray bar. Over the course of the measurement, outlet line pressure (P9015) increases from a value of 3.64 psig to 4.4 psig, starting to approach the 5 psig cracking pressure of the check valve. Internal leakage was recorded at rates ranging from 0.7 SCIM to 1.4 SCIM. Although the effects from outlet line pressure on the check valve are still believed to be minimal, a larger backpressure can also result in higher internal leakage rates due to a smaller net sealing force acting across the poppet and the seat. As such, it is believed that the most accurate value for internal leakage is found at the local minimum for outlet pressure and the active flowmeter. In the case of LLRV Leak Measurement #4, this value was 0.8 SCIM, occurring at a time value of approximately 3610s. It should be noted that although inlet line pressure is shown in the figure, it is not tabulated below.

Table 8: LLRV “LH_2” Leak Measurement #4 (3610s)

	INTERNAL LINE TEMP	TA SKIN TEMP	INTERNAL LEAKAGE	OUTLET LINE PRESSURE
Time (s)	T9010 (°F)	TEMP1 (°F)	FM1 (SCIM)	P9015 (psig)
3610	-285.6	-311.1	0.8	3.64
3620	-286.1	-311.2	1.4	3.76
3630	-286.1	-311.3	1.3	3.89
3640	-285.7	-311.2	1.4	4.00
3650	-285.0	-311.1	0.7	4.12
3660	-284.4	-311.3	0.9	4.19
3670	-283.8	-311.2	1.3	4.30
3680	-283.2	-311.2	1.1	4.40

H. LLRV “LH_2” Flow and Leak Test #5

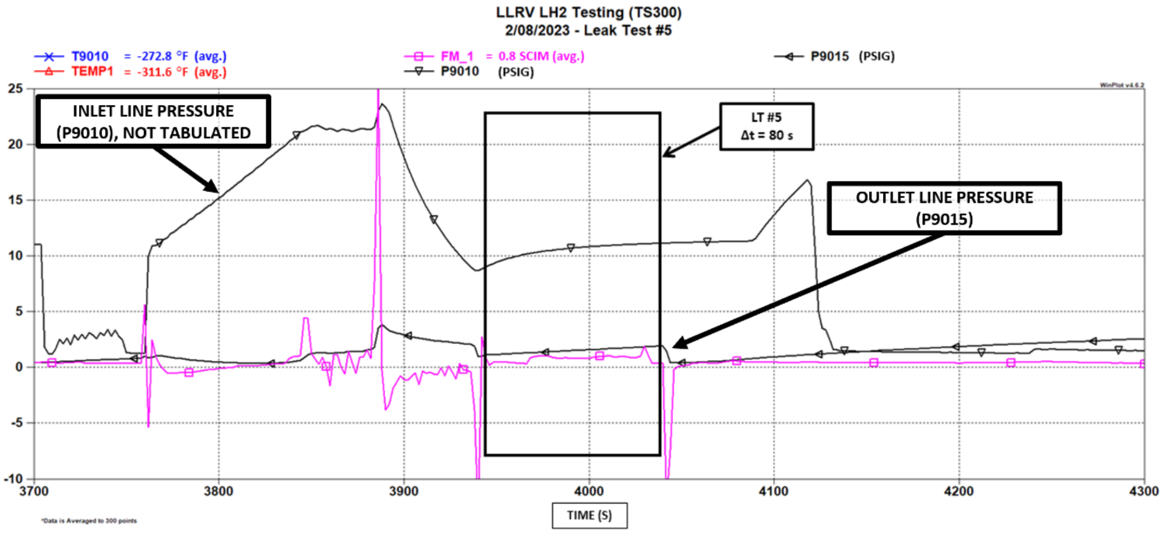


Fig. 22: LLRV Flow and Leak Test #5

For LLRV Leak Test and Measurement #5, values were recorded over a duration of approximately 80 seconds, as shown in Fig. 22. Internal line temperature (T9010) and test article skin temperature (TEMP1) are held constant due to the LN_2 spray bar. Over the course of the measurement, outlet line pressure (P9015) increases from a value of 1.14 psig to 1.75 psig, but still stays well below the 5 psig cracking pressure of the check valve. Internal leakage was recorded at rates ranging from 0.4 SCIM to 0.9 SCIM (the 2.5 SCIM value is a momentary result from opening the flowmeter). Although the effects from outlet line pressure on the check valve are believed to be minimal or non-existent, a larger backpressure can also result in higher internal leakage rates due to a smaller net sealing force acting across the poppet and the seat. As such, it is believed that the most accurate value for internal leakage is found at the local minimum for outlet pressure and the active flowmeter. In the case of LLRV Leak Measurement #5, this value was 0.5 SCIM, occurring at a time value of approximately 3950s. It should be noted that although inlet line pressure is shown in the figure, it Is not tabulated below.

Table 9: LLRV “LH_2” Leak Measurement #5 (3940s)

	INTERNAL LINE TEMP	TA SKIN TEMP	INTERNAL LEAKAGE	OUTLET LINE PRESSURE
Time (s)	**T9010 (°F)**	**TEMP1 (°F)**	**FM1 (SCIM)**	**P9015 (psig)**
3940	-273.0	-311.7	2.5	0.93
3950	-273.4	-311.7	0.5	1.14
3960	-273.9	-311.8	0.4	1.24
3970	-273.7	-311.8	0.9	1.32
3980	-273.4	-311.7	0.7	1.42
3990	-272.9	-311.7	0.7	1.49
4000	-272.4	-311.6	0.7	1.57
4010	-271.9	-311.6	0.9	1.66
4020	-271.3	-311.6	0.7	1.75

I. Summary of LLRV “LH$_2$” Flow and Leak Test Results

A summary of results from LLRV “LH$_2$” testing is shown in Table 10. A few important points are listed below:

1) Outlet line pressure (or backpressure) from the check valve may have affected the measured internal leakage rates, but impact is believed to be minimal. More substantial effects were seen later with the isolation valve and pre-valve, and will be discussed in more depth within those sections.
2) The most accurate internal leakage rates recorded for each test are believed to have occurred at (or shortly after) the local minimums for outlet pressure and the active flowmeter. These are the “Leakage” values shown in the table below, and occurred before the outlet line pressure began to approach the check valve cracking pressure.
3) Internal leakage rates measured are likely the cumulative sum of the true leakage rate, hydrogen boiloff effects, and shifts in flowmeter zero-offsets due to temperature.

Table 10: LLRV LH$_2$ Summary

	Leakage	Outlet Pressure	Notes
LT #1	≤ 0.5 SCIM	~0.3 psig (stable)	Measurement duration of 126s.
LT #2	≤ 0.5 SCIM	0.94 psig (rising)	Measurement duration of 226s.
LT #3	≤ 0.7 SCIM	1.24 psig (rising)	Measurement duration of 71s.
LT #4	≤ 0.8 SCIM	3.64 psig (rising)	Measurement duration of 77s.
LT #5	≤ 0.5 SCIM	1.14 psig (rising)	Measurement duration of 80s.

VI. Low Leakage Isolation Valve (3-Inch)

A. Test Article Description

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. 23, Fig. 24).

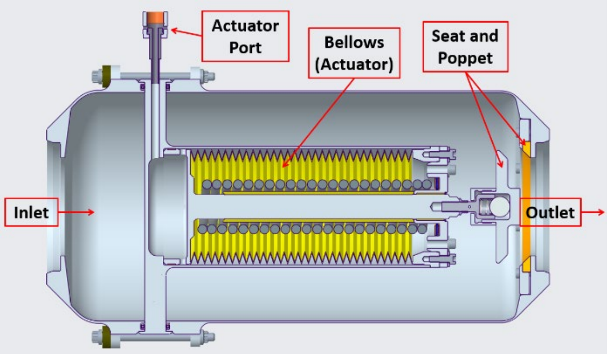


Fig. 23: LLIV Cross-Section

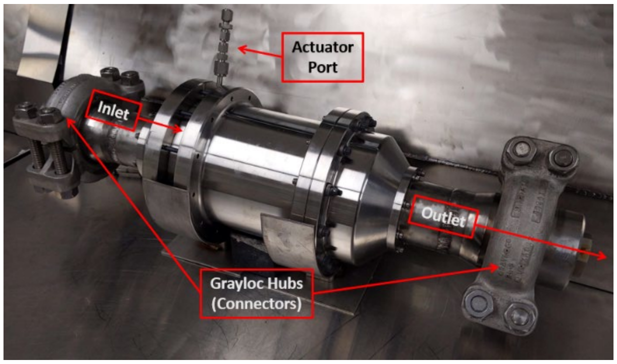


Fig. 24: LLIV Test Article

The LLIV is designed for operation down to liquid hydrogen temperatures and has a maximum design pressure of 115 psig for the main valve, and 250 psig for the actuator. Additional LLIV parameters are shown in Table 11.

Table 11: LLIV Design Parameters

Parameter	Value
Operating Temperature	-430 °F to +100 °F
Maximum Design Pressure (Valve)	115 psig
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
Internal Leakage (Goal)	≤ 1 SCIM Hydrogen @ -423 +/- 10 °F

B. LLIV LN_2 Test Series

The LLIV successfully completed the hydrostatic proof test at 55 psig, after which internal leakage rates were measured by submerging the test article 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 LN_2 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 12.

Table 12: LLIV Post-Flow Internal Leakage Rates

Flow	Actuator	Inlet	Leakage	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 pits, with material from the seat sticking to the poppet (see Fig. 25A and 25B). The cause of this damage is unknown, but likely due to excessive actuator pressure. It was also discovered that the poppet spring (see Fig. 25C) was significantly less stiff than what was required (with a rate of only 12 lbf/in, instead of 52 lbf/in). The LLIV underwent a follow-on test (see Fig. 25D) to verify whether leakage was 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 Fig. 25E. This test utilized a specialized seat that could be plugged or left open. This seat was also slightly thicker than a normal test seat. Results from this test showed no leakage in either path.

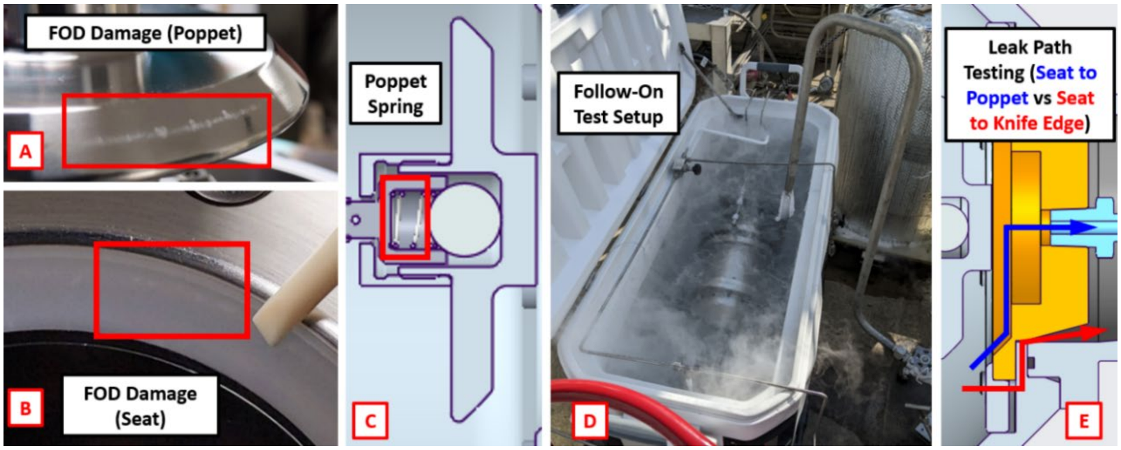


Fig. 25A through 25E (LLIV Follow-On)

The LLIV was then tested with the intent of observing the internal leakage rates after ensuring correct seat retainer values and while increasing actuator pressures to 200 psig. A new seat (with a normal thickness) was used for this test. No internal leakage was observed under ambient conditions, but a slight internal leakage of 12.4 SCIM was detected under cryogenic conditions. This indicated that seat thickness may have been playing a factor. The LLIV was then tested with a new, slightly thicker seat. Results from this test showed no leakage in either path. With corrections made to the actuator, as well as improved levels of leakage observed from LN_2 testing, the activity then proceeded to LH_2 testing at TS300.

C. LLIV LH_2 Test Series Overview

The primary objective of the LH_2 test for the LLIV was to measure the internal leakage rate through the test article after subjecting the test article to flow of liquid hydrogen (LH_2). The LLIV is shown being integrated into its test setup in Fig. 26.

Fig. 26: LLIV LH_2 Test Setup

To prevent air and moisture from entering the system (also known as "cryopumping") and impacting the operation of the LLIV, a check valve and extended vent line were installed from the vent for the actuator control valve into the burn stack duct. A check valve to prevent cryopumping was also installed downstream of the flow meters. Although these check valves were not included on the original schematic, their approximate location has been noted in Fig. 27. Both check valves were rated for 5 psig cracking pressure. Color-coded boxes have also been included, which correspond to the parameters plotted in subsequent figures.

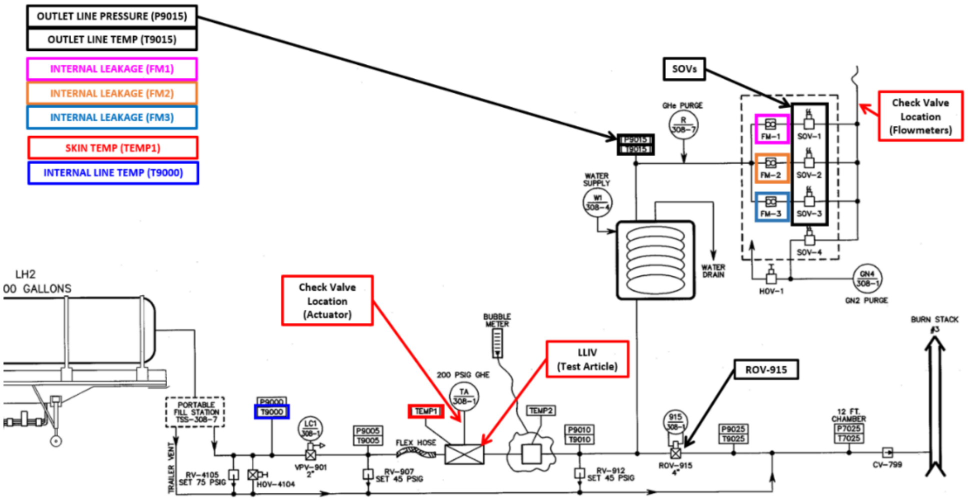


Fig. 27: LLIV LH_2 Test Schematic Details

The LLIV was cycled (opened and closed) a total of 5 times before each measurement was taken. This procedure was repeated 5 times (for a total of 25 cycles on the test article). During LH_2 flow, ROV-915 remained open (while keeping SOV-1, SOV-2, and SOV-3 closed) which routed the hydrogen from the test article to the burn stack. Once the test article was in its closed position, a leak measurement was taken by closing ROV-915, and opening the SOVs one at a time, in descending order (see Table 13). This allowed hydrogen to flow past the metering device in-line with the SOV.

Table 13: Flow Meter Capacity

Flow Meter	Solenoid	Range (SCIM)	Part Number
FM-3	SOV-3	60 - 30,500	HFM-D-301A (0-500 SLPM)
FM-2	SOV-2	0.6 - 305	HFM-D-300A (0-5 SLPM)
FM-1	SOV-1	1.2 - 61	GM50A (0-1000 SCCM)

Due to the check valve placed to prevent cryopumping, a build-up of outlet line pressure between the test article and the flowmeters would occur if ROV-915 was closed before the test article outlet line had been fully drained. This "short drain" would lead to a large initial reading of internal leakage (as seen in Leak Tests #1, #3, and #5 from Fig. 28), but was done in order to retain cryogenic temperatures for as long as possible. This internal leakage would decrease as outlet line pressure dropped, but while also seeing temperatures rise.

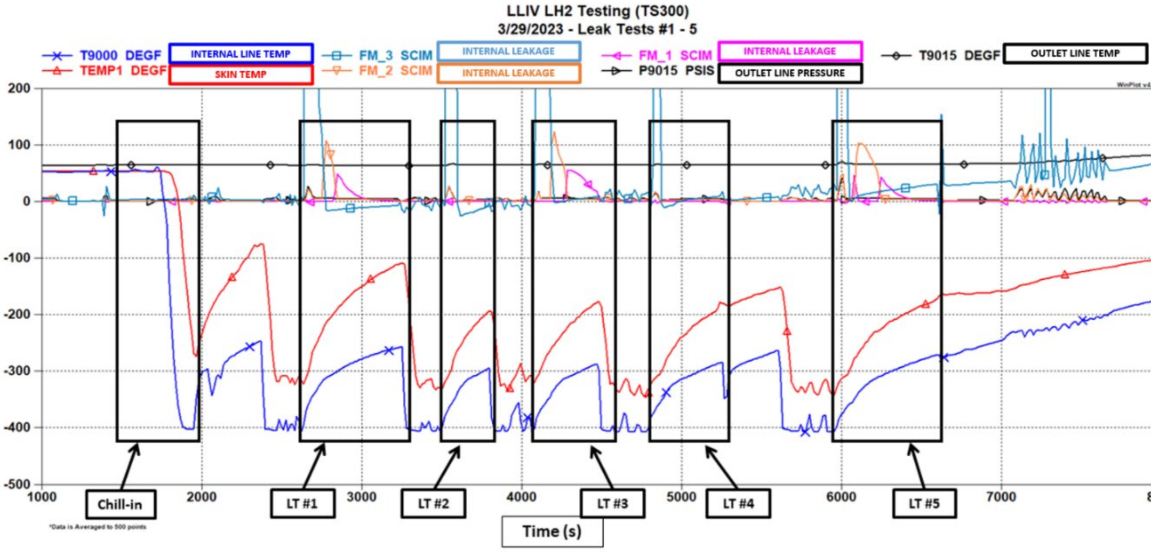


Fig. 28: Overview of LLIV LH_2 Test Data

For Leak Tests #2 and #4, ROV-915 was allowed to remain open for an extended duration (a "full drain") to enable further hydrogen drainage from the line (reducing the pressure for the purpose of internal leakage measurement). A very low leakage rate was consistently observed after this drainage; this rate would increase significantly once the pressure in the outlet line exceeded the check valve's cracking pressure. The leakage rates are likely the cumulative sum of the true leakage rate, hydrogen boiloff, and zero-shift of the flowmeters. In cases where the outlet line pressure values approach or exceed 5 psig, these rates are believed to encompass the same three factors, as well as any additional flow resulting from the check valve cracking.

Throughout the test the zero-offset of FM3 was seen to increase by approximately 20 SCIM. This change is likely due to the large capacity of the flow meter combined with the increase in ambient temperature throughout the day (as recorded between time values of 1000s and 6500s by T9015 and seen in Fig. 29). No significant shift in zero-offset was observed in FM2 and FM1 (not shown).

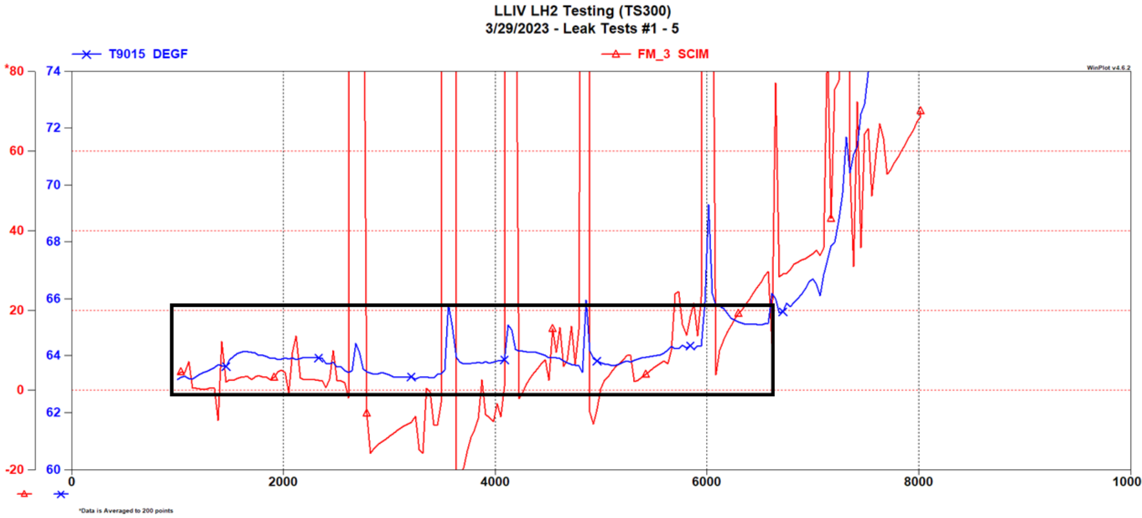


Fig. 29: LLIV FM3 Zero-Offset Shift

A correlation between the outlet line pressure and the measured internal leakage rates can be observed in the "multi-Y" plot shown in Fig. 30. The red boxes enclose time intervals where outlet line pressure (P9015) exceeds 5 psig. Leak rates recorded within the red segments often measure 50 SCIM or more, most likely indicating that additional flow is occurring from the cracking of the check valve ("CV"). The green boxes enclose time intervals where outlet line pressure falls below 5 psig. Leak rates recorded within the green segments tend to stay under 10 SCIM (or trend towards single digits). To optimize the clarity of data from leak tests in Fig. 30, any data from chill-in or valve cycling events have been visually obscured. This correlation with outlet line pressure appears to have a stronger effect upon observed leakage rates for this particular setup than temperature. A detailed look at individual tests for the LLIV is included on subsequent pages.

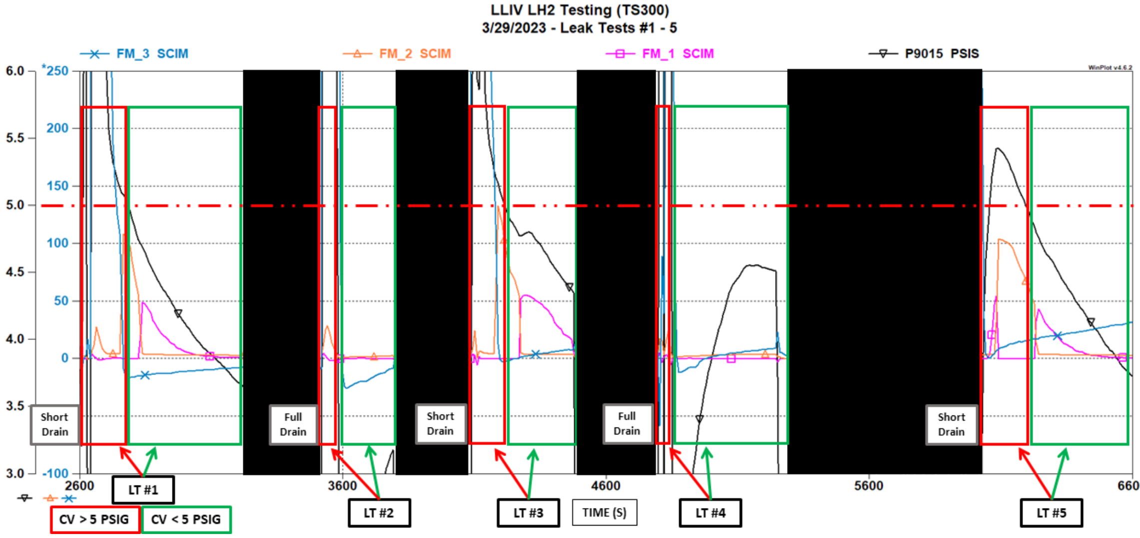


Fig. 30: LLIV Outlet Pressure and Leak Rate Correlation

D. LLIV LH₂ Flow and Leak Test #1

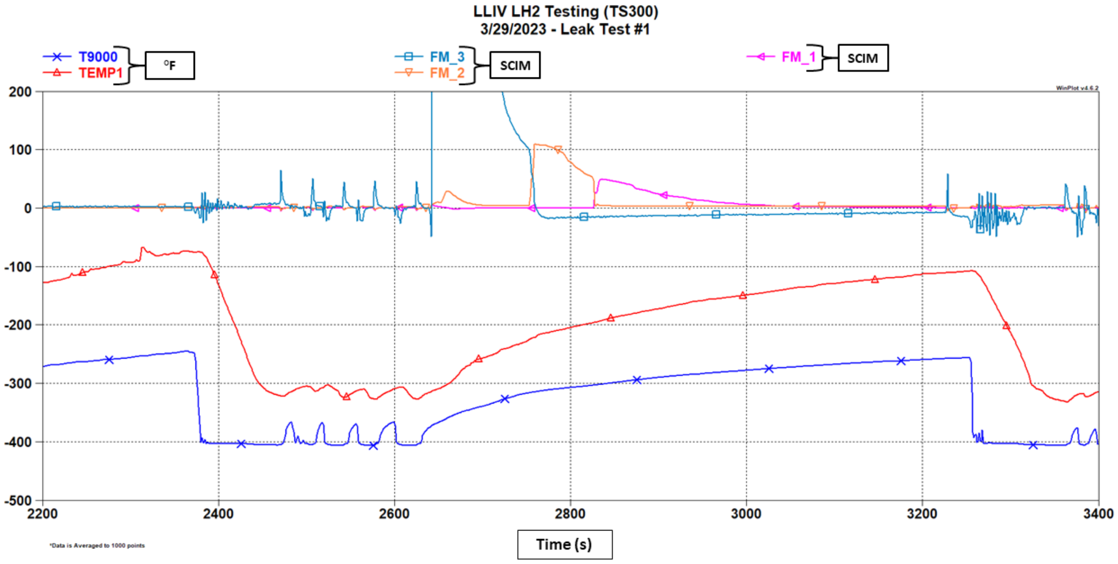


Fig. 31: LLIV Flow and Leak Test #1

For LLIV Leak Test and Measurement #1, a "short drain" process was performed, quickly closing ROV-915 in an attempt to retain cryogenic temperatures for as long as possible. Although internal leakage can be seen to decrease as temperature rises, post-test analysis revealed a much stronger correlation with outlet line pressure (as previously shown in Fig. 30). Internal leakage (bold values in "FM" columns) was seen to drop below 50 SCIM as outlet line pressure (P9015) dropped to 4.71 psig. As shown in Table 14, this event occurred at an approximate time value of 2830 seconds, with internal line temperature (T9000) at -302.5°F and test article surface temperature (TEMP1) at -194.4°F. It should be noted that this table has been separated by a horizontal line that indicates a change in time step.

Internal leakage continues to decrease as outlet line pressure drops below the 5 psig cracking pressure of the check valve. Although this reduction in internal leakage measured is largely driven by flow reduction after the check valve reseats, a lower (or decreasing) backpressure can also result in lower internal leakage rates due to a larger net sealing force acting across the poppet and the seat. As such, it is believed that the most accurate value for internal leakage is found at the local minimum for outlet pressure and the active flowmeter. In the case of LLIV Leak Measurement #1, this value was 1.0 SCIM, occurring at a time value of approximately 3130s.

Table 14: LLIV Leak Measurement #1 (2650s)

Time (s)	T9000 (°F)	TEMP1 (°F)	FM3 (SCIM)	FM2 (SCIM)	FM1 (SCIM)	P9015 (psig)	T9015 (°F)
2650	-366.4	-309.0	**8918.2**	9.3	2.3	21.87	63.93
2680	-347.4	-271.9	**5266.5**	10.1	-1.2	12.15	64.72
2710	-334.5	-251.6	**412.6**	4.1	-0.1	5.50	63.82
2740	-319.8	-233.5	**121.9**	3.9	-0.1	5.19	63.52
2770	-312.1	-214.2	-16.9	**107.3**	-0.1	5.05	63.45
2800	-307.3	-204.1	-15.0	**78.0**	-0.2	4.87	63.39
2830	-302.5	-194.4	-15.0	6.7	**31.3**	4.71	63.39
2890	-291.4	-175.0	-13.1	3.2	**27.8**	4.45	63.46
2950	-283.6	-158.6	-11.3	3.1	**12.8**	4.26	63.32
3010	-276.6	-146.7	-13.1	2.9	**5.2**	4.08	63.26
3070	-270.5	-134.6	-9.4	2.8	**2.0**	3.93	63.28
3130	-264.9	-124.4	-9.4	2.6	**1.0**	3.83	63.25
	INTERNAL LINE TEMP	TA SKIN TEMP	INTERNAL LEAKAGE	INTERNAL LEAKAGE	INTERNAL LEAKAGE	OUTLET LINE PRESSURE	AMBIENT TEMP

E. LLIV LH_2 Flow and Leak Test #2

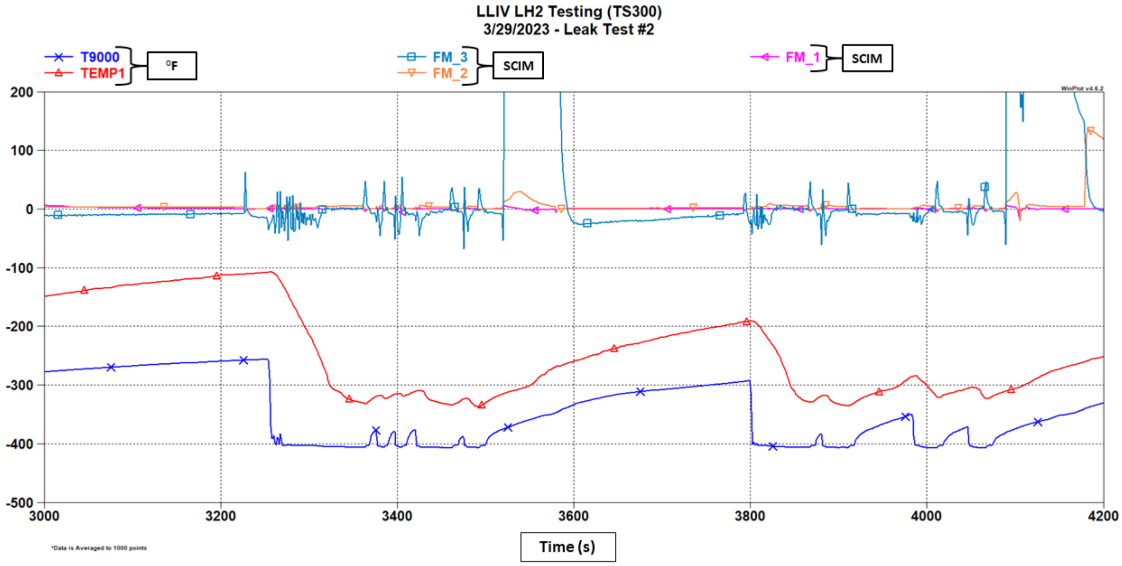


Fig. 32: LLIV Flow and Leak Test #2

For LLIV Leak Test and Measurement #2, ROV-915 was allowed to remain open for a longer period (a "full drain") in order to remove more hydrogen from the line (and reduce pressure) for leak measurements. This quickly resulted in a local minimum for outlet pressure and the active flow meter. As shown in Table 15, this event occurred at an approximate time value of 3610 seconds, with outlet line pressure (P9015) at 1.18 psig, internal line temperature (T9000) at -328.5°F and test article surface temperature (TEMP1) at -255.2°F.

Internal leakage continued to climb as outlet line pressure approached the 5 psig cracking pressure of the check valve. Although approaching or exceeding the check valve cracking pressure can inflate the measured leakage value, it is more likely that the increased leakage observed was caused by an increase in backpressure, leading to a smaller net sealing force across the poppet and seat. As such, it is believed that the most accurate value for internal leakage is found at the local minimum for outlet pressure and the active flowmeter. In the case of LLIV Leak Measurement #2, this value was 0.9 SCIM.

The collection of leak rate data was halted before P9015 reached a stable value, as the correlation between internal leakage and outlet pressure was not identified until post-test analysis. A subsequent measurement conducted in a similar manner (LLIV Leak Test #4) saw P9015 stabilizing at values around 4.5 psig, corresponding to an internal leakage rate of approximately 3.2 SCIM. For this measurement, FM1 was not activated due to a combination of rising temperatures and internal leakage rates falling within the acceptable range for FM2.

Table 15: LLIV Leak Measurement #2 (3550s)

Time (s)	T9000 (°F)	TEMP1 (°F)	FM3 (SCIM)	FM2 (SCIM)	FM1 (SCIM)	P9015 (psig)	T9015 (°F)
3550	-359.1	-300.1	8376.2	18.1	-2.1	19.17	66.08
3580	-346.2	-267.6	693.9	-0.7	-3.8	0.71	64.80
3610	-328.5	-255.2	-26.3	0.9	-0.1	1.18	64.02
3640	-318.7	-239.4	-22.5	1.2	-0.1	1.73	63.82
3670	-312.2	-230.1	-15.0	1.5	-0.1	2.15	63.75
3700	-308.1	-219.0	-16.9	1.5	-0.1	2.48	63.67
3730	-303.9	-209.4	-16.9	1.6	-0.1	2.77	63.70
3760	-299.2	-201.4	-9.4	2.0	0.0	3.02	63.71
3790	-294.5	-192.8	-7.5	2.2	-0.1	3.20	63.74
	INTERNAL LINE TEMP	TA SKIN TEMP	INTERNAL LEAKAGE	INTERNAL LEAKAGE	INTERNAL LEAKAGE	OUTLET LINE PRESSURE	AMBIENT TEMP

F. LLIV LH_2 Flow and Leak Test #3

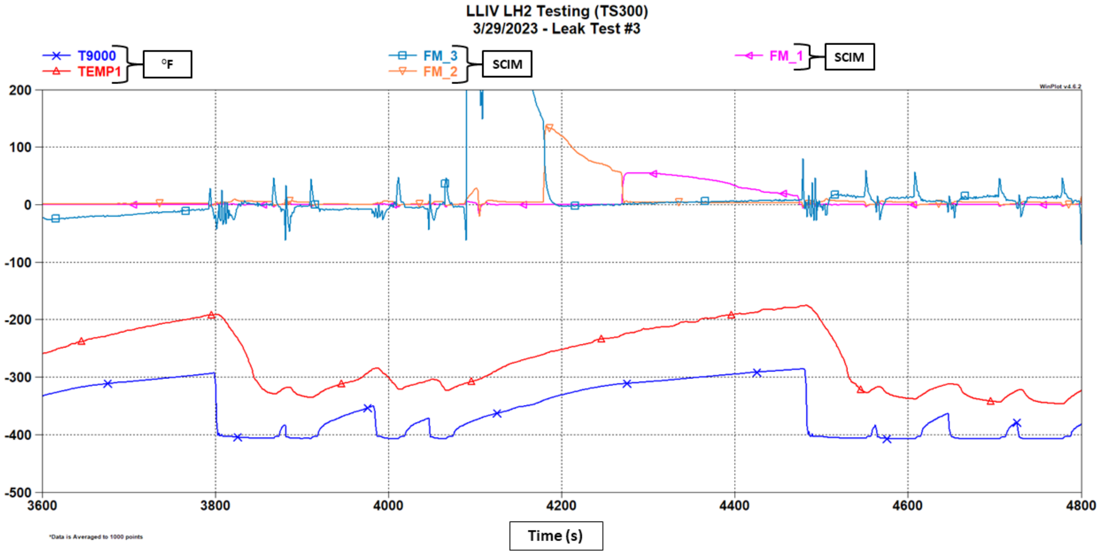


Fig. 33: LLIV Flow and Leak Test #3

For LLIV Leak Test and Measurement #3 a “short drain” process was again performed (similar to LLIV Leak Test #1). Although internal leakage does again decrease as temperature rises, there is still a much stronger correlation with outlet line pressure. Internal leakage dropped below 50 SCIM as line pressure (P9015) dropped to 4.66 psig. As shown in Table 16, this event occurred at an approximate time value of 4360 seconds, with internal line temperature (T9000) at -300.0°F and test article surface temperature (TEMP1) at -199.1°F.

Internal leakage continues to decrease as outlet line pressure drops below the 5 psig cracking pressure of the check valve. Although this reduction in internal leakage measured is largely driven by flow reduction after the check valve reseats, a lower (or decreasing) backpressure can also result in lower internal leakage rates due to a larger net sealing force acting across the poppet and the seat. As such, it is believed that the most accurate value for internal leakage is found at the local minimum for outlet pressure and the active flowmeter. In the case of LLIV Leak Measurement #3, this value was 18.1 SCIM, occurring at a time value of approximately 4460s.

The measurement was prematurely ended after approximately 340 seconds, before the internal leakage rates could decrease further. This decision was largely influenced by the presumption that there was a stronger correlation between internal leakage rate and the observed increase in temperatures. If given a similar observance time of 500 seconds, LLIV Leak Measurement #3 would likely have produced similar results to the other “short drain” tests (#1 and #5).

Table 16: LLIV Leak Measurement #3 (4120s)

Time (s)	T9000 (°F)	TEMP1 (°F)	FM3 (SCIM)	FM2 (SCIM)	FM1 (SCIM)	P9015 (psig)	T9015 (°F)
4120	-365.0	-291.6	**2635.1**	6.6	-0.2	8.05	65.47
4150	-351.9	-272.5	**363.8**	4.1	-0.1	5.49	64.49
4180	-339.3	-259.5	73.1	**132.5**	-0.2	5.20	64.17
4210	-326.9	-247.5	-5.6	**102.8**	-0.2	5.00	64.18
4240	-317.4	-235.0	-3.8	**72.1**	0.0	4.87	64.21
4300	-307.9	-216.1	5.6	3.6	**54.6**	4.81	64.19
4360	-300.0	-199.1	7.5	3.5	**44.7**	4.66	64.12
4420	-292.0	-188.1	9.4	3.2	**26.5**	4.48	64.02
4460	-287.7	-179.1	3.7	3.2	**18.1**	4.38	63.97
	INTERNAL LINE TEMP	**TA SKIN TEMP**	**INTERNAL LEAKAGE**	**INTERNAL LEAKAGE**	**INTERNAL LEAKAGE**	**OUTLET LINE PRESSURE**	**AMBIENT TEMP**

G. LLIV LH$_2$ Flow and Leak Test #4

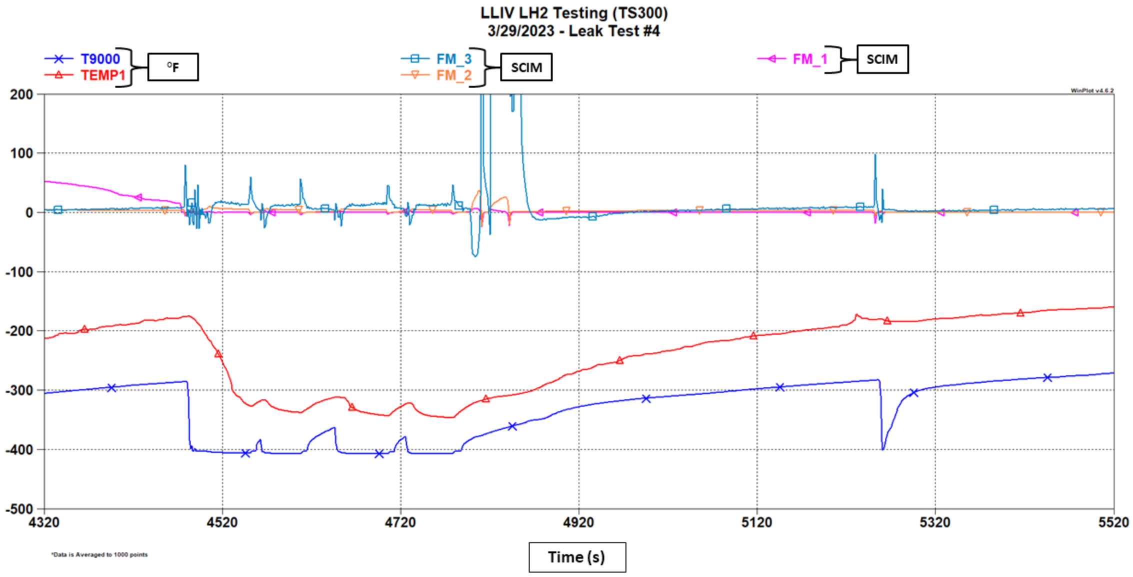
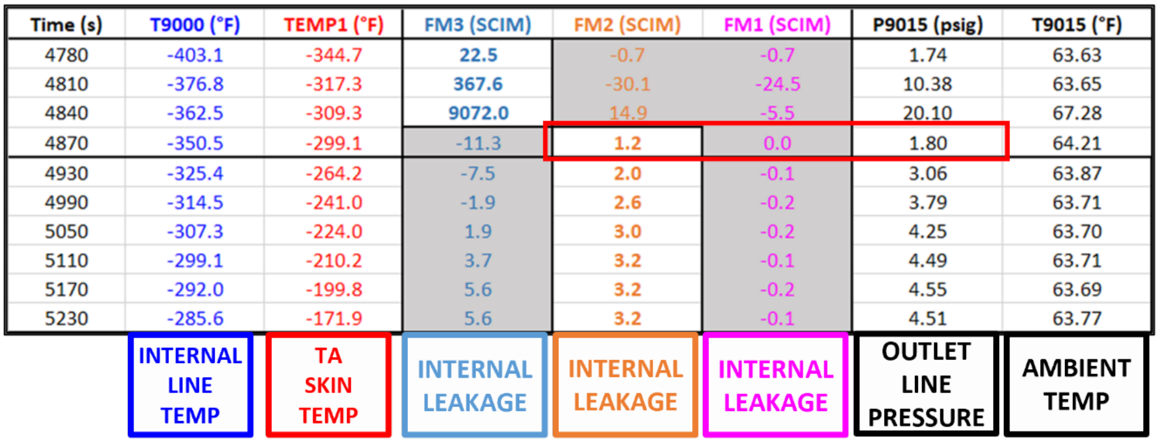


Fig. 34: LLIV Flow and Leak Test #4

For LLIV Leak Test and Measurement #4, ROV-915 was again allowed to remain open for a longer period (a "full drain") in order to remove more hydrogen from the line (and reduce pressure) for leak measurements. This quickly resulted in a local minimum for outlet pressure and the active flow meter. As shown in Table 17, this event occurred at an approximate time value of 4870 seconds, with outlet line pressure (P9015) at 1.80 psig, internal line temperature (T9000) at -350.5°F and test article surface temperature (TEMP1) at -299.1°F. It should be noted that this table has been separated by a horizontal line that indicates a change in time step.

Internal leakage continued to climb as outlet line pressure approached the 5 psig cracking pressure of the check valve. Although approaching or exceeding the check valve cracking pressure can inflate the measured leakage value, it is more likely that the increased leakage observed was caused by an increase in backpressure, leading to a smaller net sealing force across the poppet and seat. Although internal leakage rate was seen to stabilize at 3.2 SCIM, it should be noted that leakage rates measured are likely the cumulative sum of the true internal leakage rate, hydrogen boiloff effects, and shifts in the zero-offset of the flowmeter due to ambient temperature increase. As such, it is believed that the most accurate value for internal leakage is found at the local minimum for outlet pressure and the active flowmeter. In the case of LLIV Leak Measurement #4, this value was 1.2 SCIM. For this measurement, FM1 was not activated due to a combination of rising temperatures and internal leakage rates falling within the acceptable range for FM2.

Table 17: LLIV Leak Measurement #4 (4780s)



Time (s)	T9000 (°F)	TEMP1 (°F)	FM3 (SCIM)	FM2 (SCIM)	FM1 (SCIM)	P9015 (psig)	T9015 (°F)
4780	-403.1	-344.7	22.5	-0.7	-0.7	1.74	63.63
4810	-376.8	-317.3	367.6	-30.1	-24.5	10.38	63.65
4840	-362.5	-309.3	9072.0	14.9	-5.5	20.10	67.28
4870	-350.5	-299.1	-11.3	1.2	0.0	1.80	64.21
4930	-325.4	-264.2	-7.5	2.0	-0.1	3.06	63.87
4990	-314.5	-241.0	-1.9	2.6	-0.2	3.79	63.71
5050	-307.3	-224.0	1.9	3.0	-0.2	4.25	63.70
5110	-299.1	-210.2	3.7	3.2	-0.1	4.49	63.71
5170	-292.0	-199.8	5.6	3.2	-0.2	4.55	63.69
5230	-285.6	-171.9	5.6	3.2	-0.1	4.51	63.77
	INTERNAL LINE TEMP	TA SKIN TEMP	INTERNAL LEAKAGE	INTERNAL LEAKAGE	INTERNAL LEAKAGE	OUTLET LINE PRESSURE	AMBIENT TEMP

H. LLIV LH$_2$ Flow and Leak Test #5

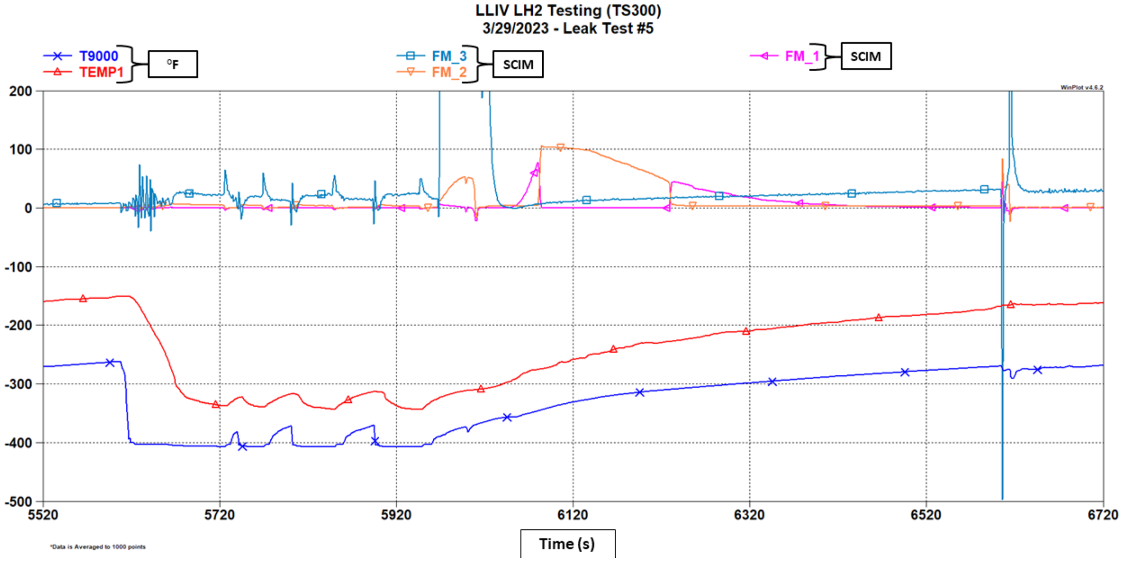


Fig. 35: LLIV Flow and Leak Test #5

For LLIV Leak Test and Measurement #5 a "short drain" process was again performed (similar to LLIV Leak Test #1 and #3). Although internal leakage does again decrease as temperature rises, there is still a much stronger correlation with outlet line pressure. Internal leakage dropped below 50 SCIM as line pressure (P9015) dropped below 4.86 psig. As shown in Table 18, this event occurred shortly after a time value of 6220 seconds, with internal line temperature (T9000) at -310.8°F and test article surface temperature (TEMP1) at -229.5°F.

Internal leakage continues to decrease as outlet line pressure drops below the 5 psig cracking pressure of the check valve. Although this reduction in internal leakage is largely driven by flow reduction after the check valve reseats, a lower (or decreasing) backpressure can also result in lower internal leakage rates due to a larger net sealing force acting across the poppet and seat. As such, it is believed that the most accurate value for internal leakage is found at the local minimum for outlet pressure and the active flowmeter. In the case of LLIV Leak Measurement #5, this value was 0.8 SCIM, occurring at a time value of approximately 6520 seconds.

Table 18: LLIV Leak Measurement #5 (5980s)

Time (s)	T9000 (°F)	TEMP1 (°F)	FM3 (SCIM)	FM2 (SCIM)	FM1 (SCIM)	P9015 (psig)	T9015 (°F)
5980	-381.2	-317.5	**11579.6**	35.1	3.4	28.25	69.85
6010	-368.8	-310.0	**2974.6**	-20.6	-24.4	2.86	67.69
6040	-357.3	-300.1	1.9	3.6	-0.1	4.62	66.05
6100	-337.3	-268.4	13.1	**102.9**	-0.3	5.40	65.72
6160	-320.6	-245.4	13.1	**85.8**	-0.3	5.16	65.57
6220	-310.8	-229.5	18.7	**50.4**	-0.4	4.86	65.26
6280	-303.1	-214.5	18.7	3.2	**26.6**	4.61	65.25
6340	-296.0	-206.8	20.6	3.1	**12.5**	4.42	65.08
6400	-289.1	-196.6	24.4	2.9	**5.7**	4.24	65.13
6460	-282.8	-187.8	28.1	2.8	**2.2**	4.07	65.13
6520	-277.2	-181.9	28.1	2.6	**0.8**	3.90	65.09
	INTERNAL LINE TEMP	**TA SKIN TEMP**	**INTERNAL LEAKAGE**	**INTERNAL LEAKAGE**	**INTERNAL LEAKAGE**	**OUTLET LINE PRESSURE**	**AMBIENT TEMP**

I. Summary of LLIV LH_2 Flow and Leak Test Results

A summary of results from LLIV LH_2 testing is shown in Table 19. A few important points are listed below:

1) Outlet line pressure (or backpressure) from the check valve likely affected the measured internal leakage rates, primarily acting to inflate the values recorded.
2) The most accurate internal leakage rates recorded for each test are believed to have occurred at (or shortly after) the local minimums for outlet pressure and the active flowmeter. These are the "Leakage" values shown in the table below, and occurred before the outlet line pressure began to approach the check valve cracking pressure.
3) Internal leakage rates recorded at or above 5 psig were likely exaggerated by additional flow introduced by the check valve cracking.
4) Internal leakage rates observed on the "Short Drain" tests (LT#1, 3, and 5), were further exaggerated by a significant increase in hydrogen boiloff versus what was seen on "Full Drain" tests.
5) Internal leakage rates measured are likely the cumulative sum of the true leakage rate, hydrogen boiloff effects, and shifts in flowmeter zero-offsets due to temperature.

Table 19: LLIV LH_2 Summary

	Leakage	Outlet Pressure	Notes
LT #1	≤ 1.0 SCIM	3.83 psig (dropping)	"Short Drain". Test Length ≈ 500s.
LT #2	≤ 0.9 SCIM	1.18 psig (rising)	"Full Drain". Test Length ≈ 250s.
LT #3	≤ 18.1 SCIM	4.38 psig (dropping)	"Short Drain". Test Length ≈ 300s. Likely ended too soon.
LT #4	≤ 1.2 SCIM	1.80 psig (rising)	"Full Drain".
LT #5	≤ 0.8 SCIM	3.90 psig (dropping)	"Short Drain". Test Length ≈ 500s.

VII. Large Pre-Valve (8-Inch)

A. Test Article Description

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).

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. 36, Fig. 37). The test article utilizes a pair of solenoid valves (not shown in images) as 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.

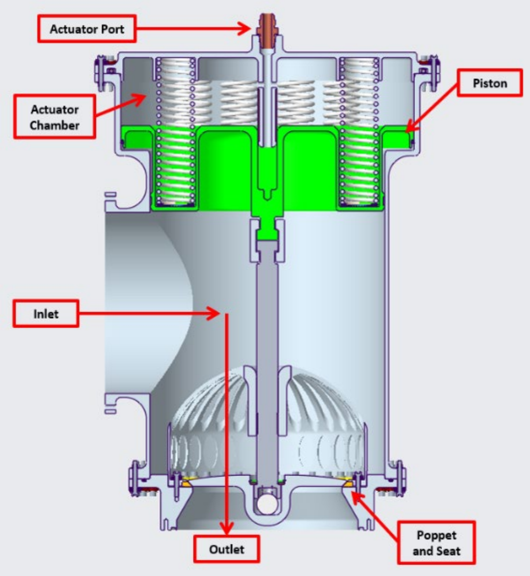


Fig. 36: LPV Cross-Section

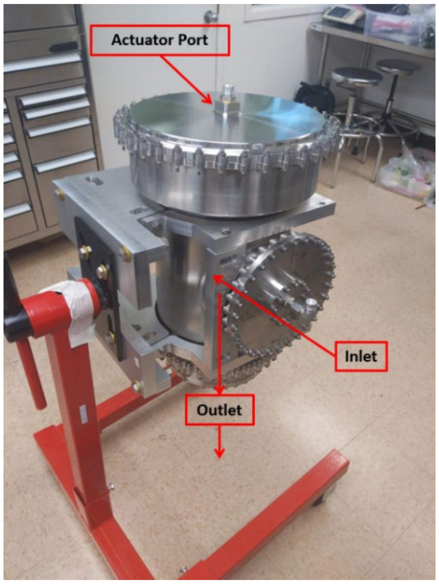


Fig. 37: LPV in Assembly Stand

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 20.

Table 20: 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
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. 38). 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**).

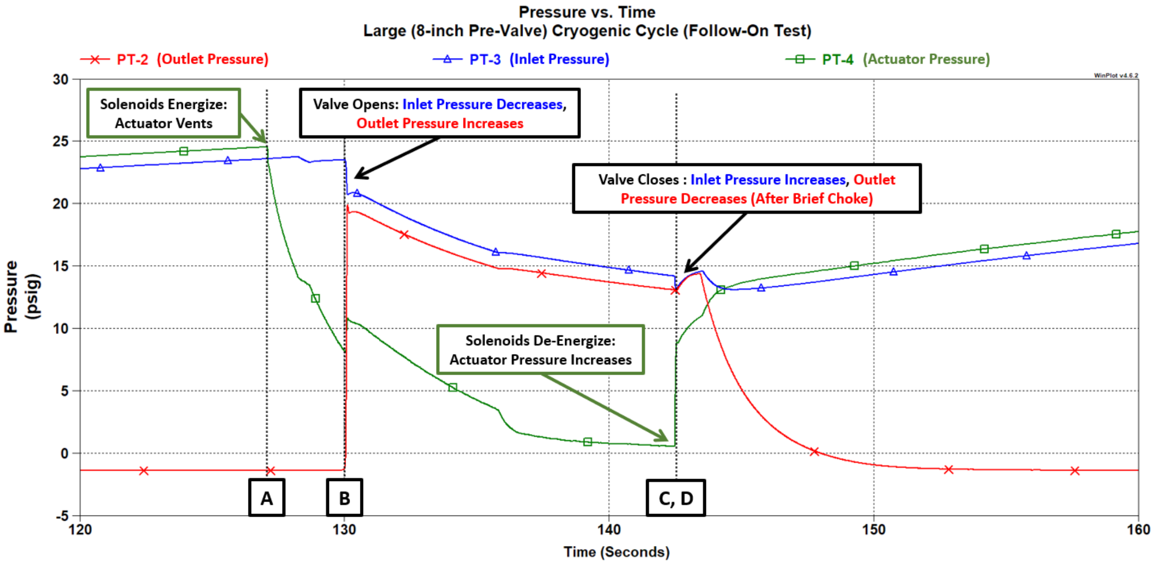


Fig. 38: Pressure Levels During an LPV Cycle

B. LPV LN$_2$ Test Series

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. 39), so a pressure decay check was performed as well, monitoring for any pressure drop over the course of 10 minutes.

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. 40).

Fig. 39: LPV Test Setup (LN_2)

Fig. 40: Dual Instrument Manifold

During initial testing, the LPV demonstrated internal leakage rates that, although much lower than similarly-sized valves, were higher than expected (Table 21).

Table 21: 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 22).

Table 22: 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

With corrections made to the actuator, as well as improved levels of leakage observed from LN_2 testing, the activity then proceeded to LH_2 testing at TS300.

C. LPV LH_2 Test Series Overview

The primary objective of the LH_2 test for the LPV was to measure the internal leakage rate through the test article after subjecting the test article to flow of liquid hydrogen (LH_2). The LPV is shown in its test setup in Fig. 41 and Fig. 42.

Fig. 41: LPV Prior to LH_2 Test

Fig. 42: LPV Post LH_2 Test

To prevent air and moisture from entering the system (also known as "cryopumping") and impacting the operation of the LPV, a check valve (rated for 5 psig cracking pressure) was installed downstream of the flow meters. Although this check valve was not included on the original schematic, its approximate location has been noted in Fig. 43. Color-coded boxes have also been included, which correspond to the parameters plotted in subsequent figures.

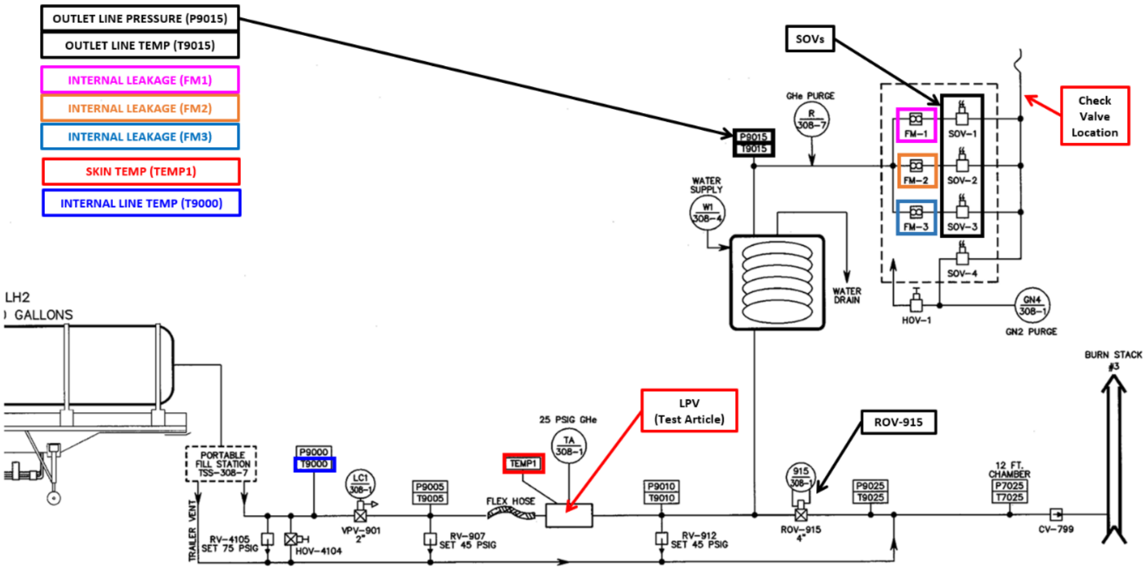


Fig. 43: LPV LH₂ Test Schematic Details

The LPV was cycled (opened and closed) a total of 5 times before each measurement was taken. This procedure was repeated 5 times (for a total of 25 cycles on the test article). During LH_2 flow, ROV-915 remained open (while SOV-1, SOV-2, and SOV-3 were closed) which routed the hydrogen from the test article to the burn stack. Once the test article was closed, a leak measurement was taken by closing ROV-915, and opening the SOVs one at a time, in descending order (see Table 23). This allowed hydrogen to flow past the metering device in-line with the SOV.

Table 23: Flow Meter Capacity

Flow Meter	Solenoid	Range (SCIM)	Part Number
FM-3	SOV-3	60 - 30,500	HFM-D-301A (0-500 SLPM)
FM-2	SOV-2	0.6 - 305	HFM-D-300A (0-5 SLPM)
FM-1	SOV-1	1.2 - 61	GM50A (0-1000 SCCM)

Due to the check valve placed to prevent cryopumping, a build-up of outlet line pressure between the test article and the flowmeters would occur if ROV-915 was closed before the test article outlet line had been fully drained. This "short drain" would lead to a large initial reading of internal leakage (as seen in Leak Test #4 in Fig. 44), but was done in order to retain cryogenic temperatures for as long as possible. This internal leakage would decrease as outlet line pressure dropped, but while also seeing temperatures rise.

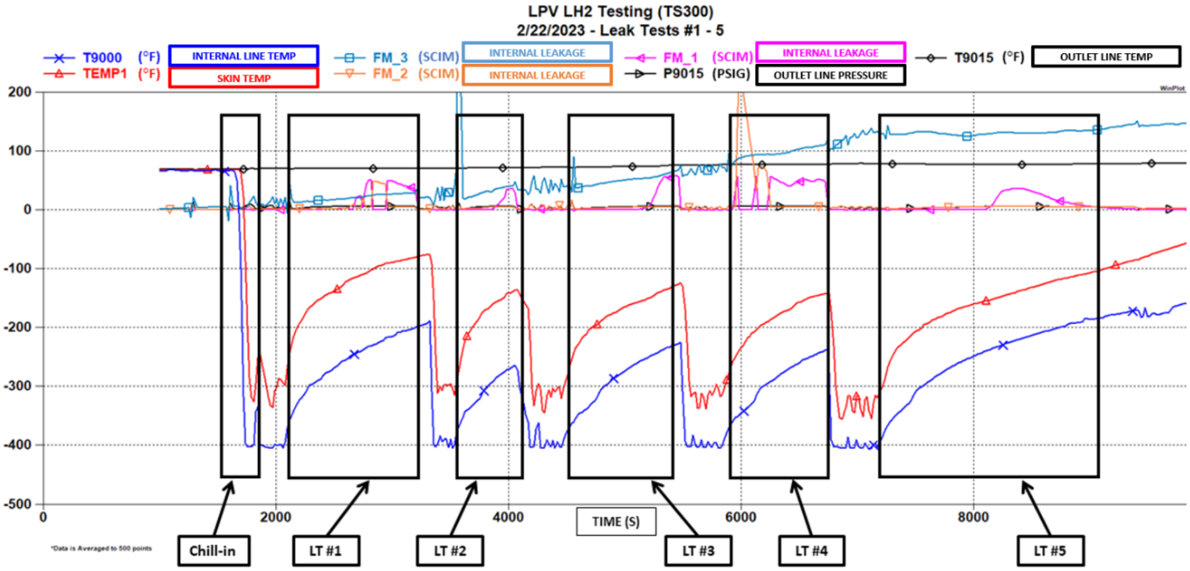


Fig. 44: Overview of LPV LH_2 Test Data

For Leak Tests #1, #2, #3, and #5, ROV-915 was allowed to remain open for an extended duration (a "full drain") to enable further hydrogen drainage from the outlet line (reducing the pressure for the purpose of internal leakage measurement). A very low leakage rate was consistently observed after this drainage; this rate would increase significantly once the pressure in the outlet line exceeded the check valve's cracking pressure. The leakage rates are likely the cumulative sum of the true leakage rate, hydrogen boiloff, and zero-shift of the flowmeters. In cases where the outlet line pressure values approach or exceed 5 psig, these rates are believed to encompass the same three factors, as well as any additional flow resulting from the check valve cracking.

Throughout the test, the zero-offset of FM3 was seen to increase by approximately 150 SCIM. This change is likely due to the large capacity of the flow meter combined with the increase in ambient temperature throughout the day (as recorded by T9015, and seen in Fig. 45). FM2 (not shown) demonstrated a similar but reduced effect, increasing by approximately 5 SCIM over the same period. No significant shift in zero-offset was observed in FM1.

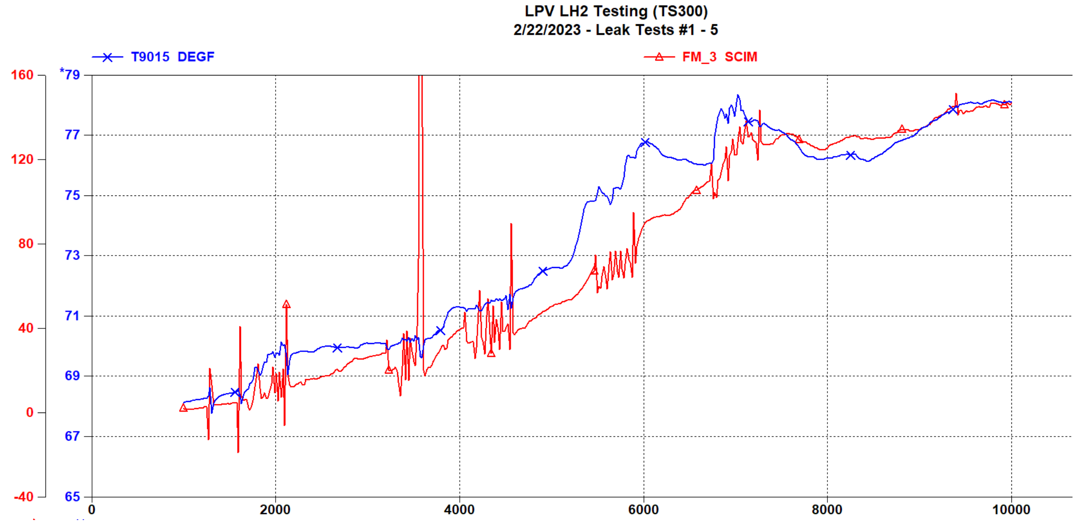


Fig. 45: LPV FM3 Zero-Offset Shift

A correlation between the outlet line pressure and the measured internal leakage rates can be observed in the “multi-Y” plot shown in Fig. 46. The red boxes enclose time intervals where outlet line pressure (P9015) exceeds 5 psig. Leak rates recorded within the red segments often measure 30 SCIM or more, most likely indicating that additional flow is occurring from the cracking of the check valve (“CV”). The green boxes enclose time intervals where outlet line pressure falls below psig. Leak rates recorded within the green segments tend to stay under 10 SCIM (or trend towards single digits). To optimize the clarity of data from leak tests in Fig. 46, any data from chill-in or valve cycling events have been visually obscured. This correlation with outlet line pressure appears to have a stronger effect upon observed leakage rates for this particular setup than temperature. A detailed look at individual tests for the LPV is included on subsequent pages.

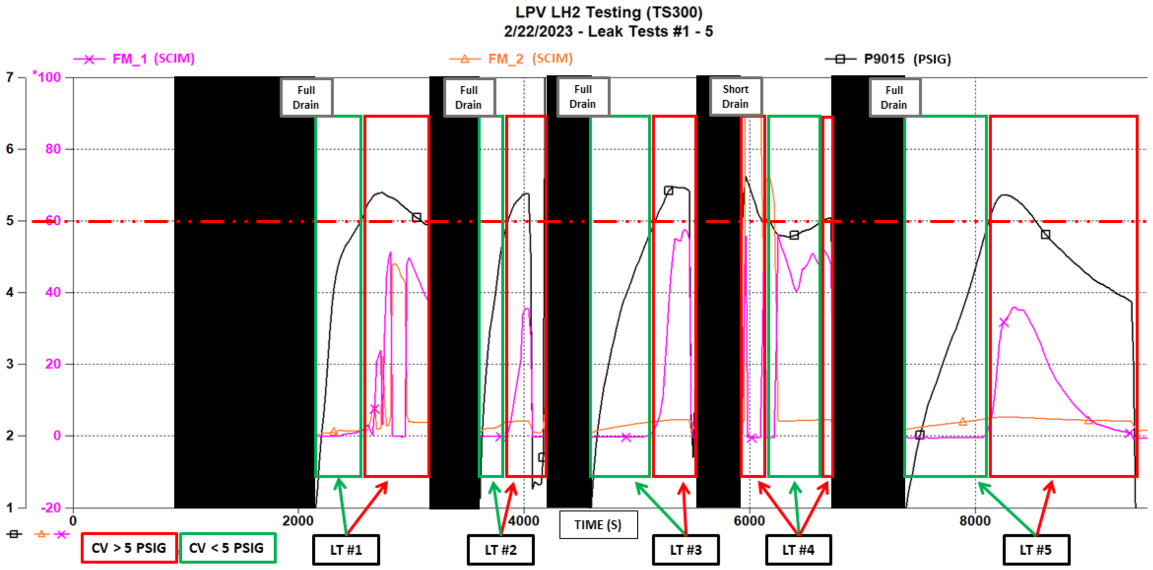


Fig. 46: LPV Outlet Pressure and Leak Rate Correlation

D. LPV LH$_2$ Flow and Leak Test #1

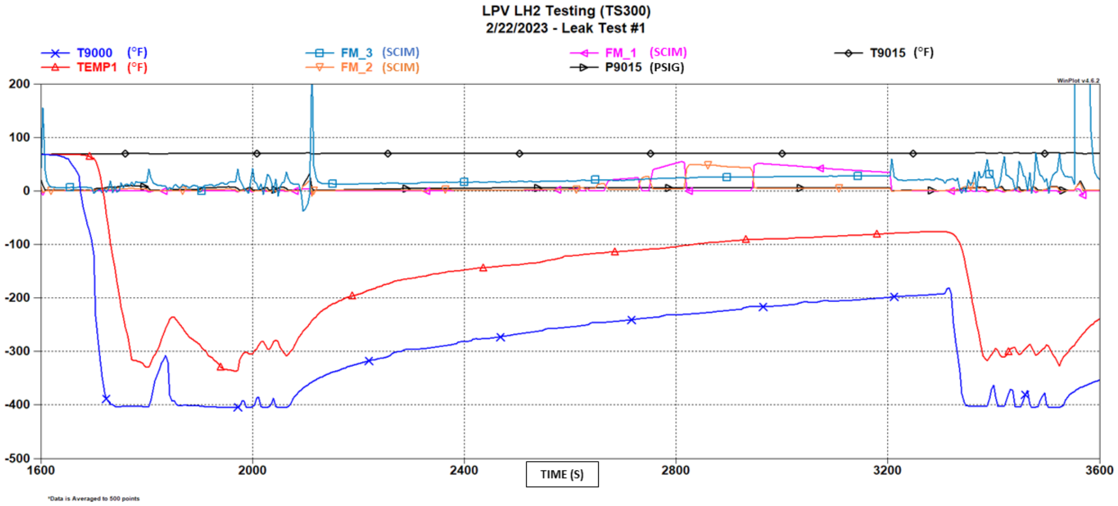


Fig. 47: LPV Flow and Leak Test #1

For LPV Leak Test and Measurement #1, ROV-915 was allowed to remain open for an extended duration (a “full drain”) in order to remove more hydrogen from the line (and reduce pressure) for leak measurements. This quickly resulted in a local minimum for outlet pressure and the active flow meter. As shown in Table 24, this event occurred at an approximate time value of approximately 2150 seconds, with outlet line pressure (P9015) at 0.92 psig, internal line temperature (T9000) at -338.8°F and test article surface temperature (TEMP1) at -211.0°F.

Table 24: LPV LH$_2$ Leak Measurement #1 (2150s)

Time (s)	T9000 (°F)	TEMP1 (°F)	FM3 (SCIM)	FM2 (SCIM)	FM1 (SCIM)	P9015 (psig)	T9015 (°F)
2135	-344.7	-219.8	18.7	0.2	-0.2	0.99	69.45
2140	-342.2	-217.1	16.9	0.2	-0.2	0.96	69.48
2145	-340.7	-214.2	7.5	0.2	-0.2	0.94	69.53
2150	-338.8	-211.0	15.0	0.2	-0.2	0.92	69.66
2155	-337.4	-208.7	9.4	0.4	-0.1	1.12	69.60
2160	-335.6	-206.4	9.4	0.4	-0.1	1.25	69.70
2165	-333.6	-204.6	15.0	0.4	-0.1	1.37	69.77

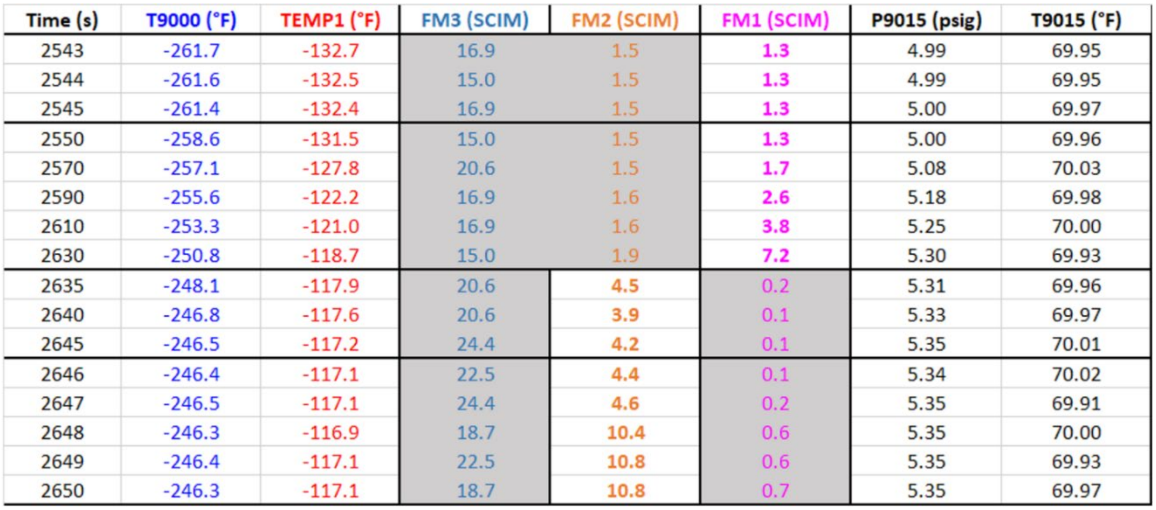
As shown in Table 25, internal leakage began to climb as outlet line pressure approached the 5 psig cracking pressure of the check valve. Although approaching or exceeding the check valve cracking pressure can inflate the measured leakage value, it is more likely that the increased leakage observed in this section was caused by an increase in backpressure, leading to a smaller net sealing force across the poppet and seat. As such, it is believed that the most accurate value for internal leakage is found at the local minimum for outlet pressure and the active flowmeter. In the case of LPV Leak Measurement #1, this value was 0.4 SCIM (shown in Table 24).

Table 25: LPV LH$_2$ Leak Measurement #1 (2360s)

Time (s)	T9000 (°F)	TEMP1 (°F)	FM3 (SCIM)	FM2 (SCIM)	FM1 (SCIM)	P9015 (psig)	T9015 (°F)
2360	-289.5	-152.5	11.2	1.6	-0.2	4.47	69.87
2365	-288.8	-151.5	15.0	1.6	-0.2	4.48	69.85
2370	-288.2	-151.1	13.1	1.7	-0.2	4.51	69.82
2375	-287.4	-151.0	13.1	1.6	0.0	4.53	69.81
2380	-286.7	-150.2	15.0	1.3	0.4	4.54	69.78
2385	-283.3	-149.5	20.6	1.3	0.4	4.56	69.82
2390	-281.5	-149.1	18.7	1.3	0.4	4.58	69.84

As shown in Table 26, line pressure (P9015) reached a value of 5.00 psig at a time value of 2545 seconds. This pressure corresponds with the rated cracking pressure for the check valve. It is also the point at which the rate of internal leakage increase begins to accelerate, also seeing a significant increase as P9015 reaches 5.35 psig. It should be noted that this table has been separated by horizontal lines that indicate a change in time step.

Table 26: LPV LH_2 Leak Measurement #1 (2543s)

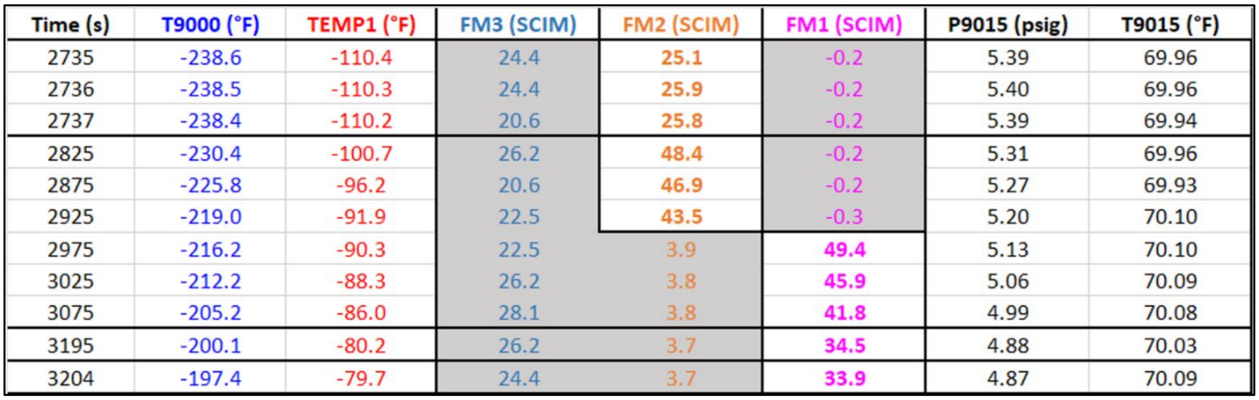


Time (s)	T9000 (°F)	TEMP1 (°F)	FM3 (SCIM)	FM2 (SCIM)	FM1 (SCIM)	P9015 (psig)	T9015 (°F)
2543	-261.7	-132.7	16.9	1.5	**1.3**	4.99	69.95
2544	-261.6	-132.5	15.0	1.5	**1.3**	4.99	69.95
2545	-261.4	-132.4	16.9	1.5	**1.3**	5.00	69.97
2550	-258.6	-131.5	15.0	1.5	**1.3**	5.00	69.96
2570	-257.1	-127.8	20.6	1.5	**1.7**	5.08	70.03
2590	-255.6	-122.2	16.9	1.6	**2.6**	5.18	69.98
2610	-253.3	-121.0	16.9	1.6	**3.8**	5.25	70.00
2630	-250.8	-118.7	15.0	1.9	**7.2**	5.30	69.93
2635	-248.1	-117.9	20.6	**4.5**	0.2	5.31	69.96
2640	-246.8	-117.6	20.6	**3.9**	0.1	5.33	69.97
2645	-246.5	-117.2	24.4	**4.2**	0.1	5.35	70.01
2646	-246.4	-117.1	22.5	**4.4**	0.1	5.34	70.02
2647	-246.5	-117.1	24.4	**4.6**	0.2	5.35	69.91
2648	-246.3	-116.9	18.7	**10.4**	0.6	5.35	70.00
2649	-246.4	-117.1	22.5	**10.8**	0.6	5.35	69.93
2650	-246.3	-117.1	18.7	**10.8**	0.7	5.35	69.97

Line pressure (P9015) reached a maximum value of 5.40 psig at approximately 2736s, as shown in Table 27. This event corresponded with an internal line temperature of -238.5°F, a test article surface temperature (TEMP1) of -110.3°F, and an FM2 reading of 25.9 SCIM. It should be noted that this table has been separated by horizontal lines that indicate a change in time step, and that the maximum flow rate measured (55.2 SCIM) occurred in-between time steps, at a time value of 2815 seconds and a line pressure value of 5.33 psig.

Towards the end of the measurement, line pressure and internal leakage rate began to drop, reaching values of 4.87 psig and 33.9 SCIM (respectively). The collection of leak rate data was halted before P9015 reached a stable value, as the correlation between internal leakage and outlet pressure was not identified until post-test analysis.

Table 27: LPV LH_2 Leak Measurement #1 (2735s)



Time (s)	T9000 (°F)	TEMP1 (°F)	FM3 (SCIM)	FM2 (SCIM)	FM1 (SCIM)	P9015 (psig)	T9015 (°F)
2735	-238.6	-110.4	24.4	**25.1**	-0.2	5.39	69.96
2736	-238.5	-110.3	24.4	**25.9**	-0.2	5.40	69.96
2737	-238.4	-110.2	20.6	**25.8**	-0.2	5.39	69.94
2825	-230.4	-100.7	26.2	**48.4**	-0.2	5.31	69.96
2875	-225.8	-96.2	20.6	**46.9**	-0.2	5.27	69.93
2925	-219.0	-91.9	22.5	**43.5**	-0.3	5.20	70.10
2975	-216.2	-90.3	22.5	3.9	**49.4**	5.13	70.10
3025	-212.2	-88.3	26.2	3.8	**45.9**	5.06	70.09
3075	-205.2	-86.0	28.1	3.8	**41.8**	4.99	70.08
3195	-200.1	-80.2	26.2	3.7	**34.5**	4.88	70.03
3204	-197.4	-79.7	24.4	3.7	**33.9**	4.87	70.09

E. LPV LH$_2$ Flow and Leak Test #2

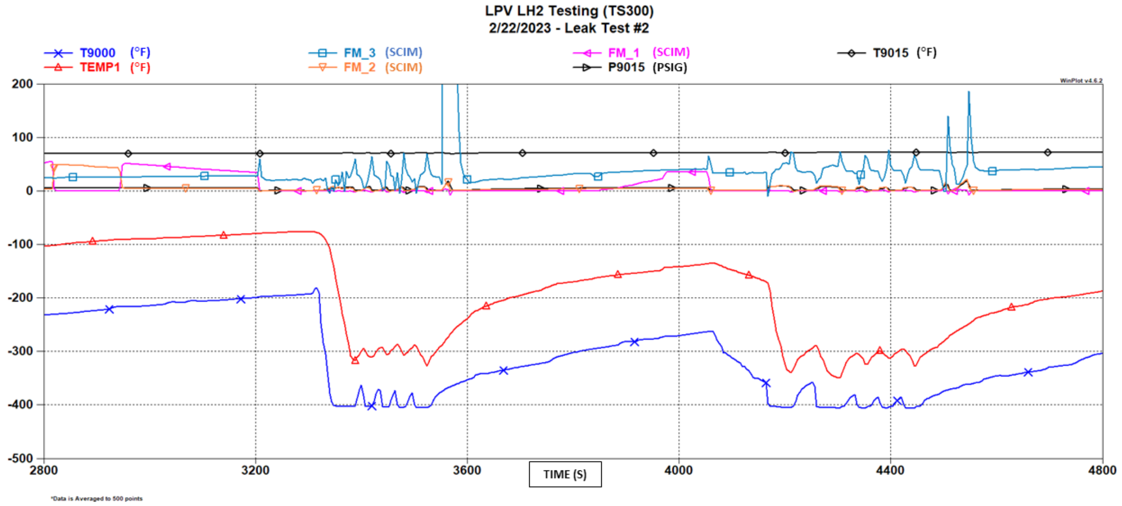
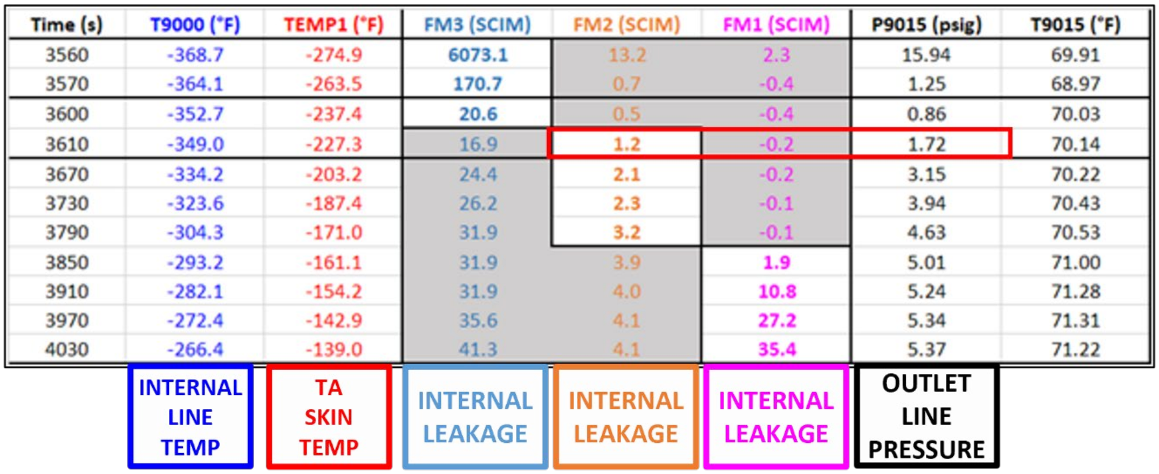


Fig. 48: LPV Flow and Leak Test #2

For LPV Leak Test and Measurement #2, ROV-915 was again allowed to remain open (a "full drain") in order to remove more hydrogen from the line (and reduce pressure) for leak measurements. This quickly resulted in a local minimum for outlet pressure and the active flow meter. As shown in Table 28, this event occurred at an approximate time value of 3610s, with outlet line pressure (P9015) at 1.72 psig, internal line temperature (T9000) at -349.0°F, and test article surface temperature (TEMP1) at -227.3°F . It should be noted that this table has been separated by horizontal lines that indicate a change in time step.

Internal leakage continued to climb as outlet line pressure approached the 5 psig cracking pressure of the check valve. Although approaching or exceeding the check valve cracking pressure can inflate the measured leakage value, it is more likely that the increased leakage observed at this point was caused by an increase in backpressure, leading to a smaller net sealing force across the poppet and seat. As such, it is believed that the most accurate value for internal leakage is found at the local minimum for outlet pressure and the active flowmeter. In the case of LPV Leak Measurement #2, this value was 1.2 SCIM. The outlet line pressure (P9015) reached a value of 5.01 psig at approximately 3850 seconds. At this point, the rate of increase in FM1 values began to accelerate significantly, likely indicating the check valve cracking.

Table 28: LPV LH$_2$ Leak Measurement #2 (3560s)



Time (s)	T9000 (°F)	TEMP1 (°F)	FM3 (SCIM)	FM2 (SCIM)	FM1 (SCIM)	P9015 (psig)	T9015 (°F)
3560	-368.7	-274.9	6073.1	13.2	2.3	15.94	69.91
3570	-364.1	-263.5	170.7	0.7	-0.4	1.25	68.97
3600	-352.7	-237.4	20.6	0.5	-0.4	0.86	70.03
3610	-349.0	-227.3	16.9	1.2	-0.2	1.72	70.14
3670	-334.2	-203.2	24.4	2.1	-0.2	3.15	70.22
3730	-323.6	-187.4	26.2	2.3	-0.1	3.94	70.43
3790	-304.3	-171.0	31.9	3.2	-0.1	4.63	70.53
3850	-293.2	-161.1	31.9	3.9	1.9	5.01	71.00
3910	-282.1	-154.2	31.9	4.0	10.8	5.24	71.28
3970	-272.4	-142.9	35.6	4.1	27.2	5.34	71.31
4030	-266.4	-139.0	41.3	4.1	35.4	5.37	71.22
	INTERNAL LINE TEMP	TA SKIN TEMP	INTERNAL LEAKAGE	INTERNAL LEAKAGE	INTERNAL LEAKAGE	OUTLET LINE PRESSURE	

F. LPV LH₂ Flow and Leak Test #3

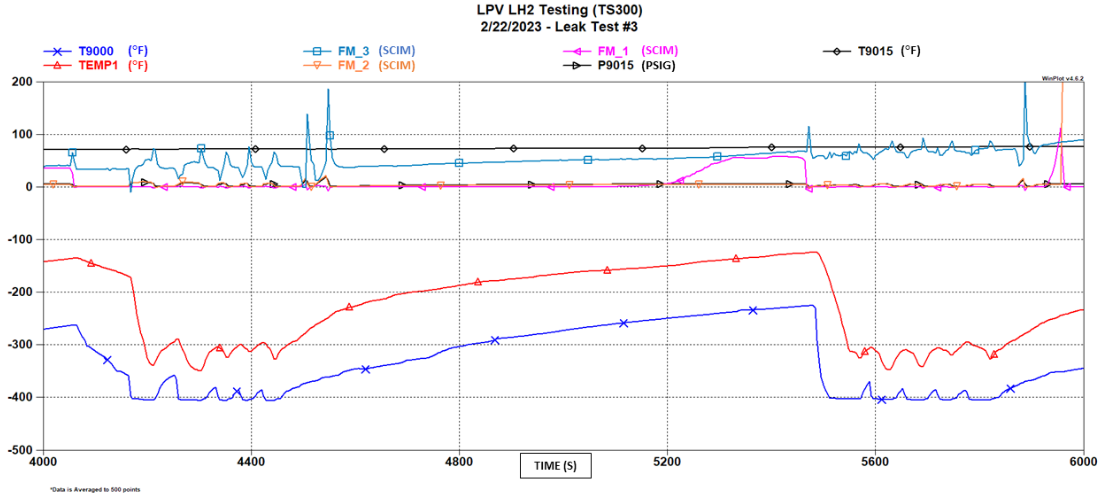
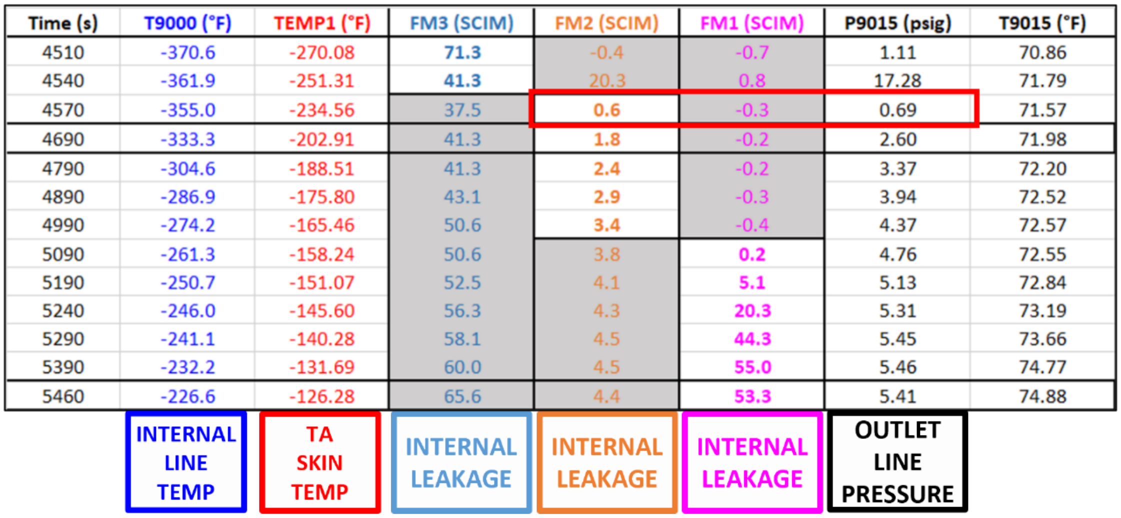


Fig. 49: LPV Flow and Leak Test #3

For LPV Leak Test and Measurement #3, ROV-915 was again allowed to remain open (a "full drain") in order to remove more hydrogen from the line (and reduce pressure) for leak measurements. This again resulted in a local minimum for outlet pressure and the active flow meter. As shown in Table 29, this event occurred at an approximate time value of 4570s, with outlet line pressure (P9015) at 0.69 psig, internal line temperature (T9000) -355.0°F, and test article surface temperature (TEMP1) at -234.56 It should be noted that this table has been separated by horizontal lines that indicate a change in time step.

Internal leakage continued to climb as outlet line pressure approached the 5 psig cracking pressure of the check valve. Although approaching or exceeding the check valve cracking pressure can inflate the measured leakage value, it is more likely that the increased leakage observed at this point was caused by an increase in backpressure, leading to a smaller net sealing force across the poppet and seat. As such, it is believed that the most accurate value for internal leakage is found at the local minimum for outlet pressure and the active flowmeter. In the case of LPV Leak Measurement #3, this value was 0.6 SCIM. The outlet line pressure (P9015) reached a value of 5.13 psig at approximately 5190 seconds. At this point, the rate of increase in FM1 values began to accelerate significantly, likely indicating the check valve cracking.

Table 29: LPV LH₂ Leak Measurement #3 (4510s)



Time (s)	T9000 (°F)	TEMP1 (°F)	FM3 (SCIM)	FM2 (SCIM)	FM1 (SCIM)	P9015 (psig)	T9015 (°F)
4510	-370.6	-270.08	71.3	-0.4	-0.7	1.11	70.86
4540	-361.9	-251.31	41.3	20.3	0.8	17.28	71.79
4570	-355.0	-234.56	37.5	0.6	-0.3	0.69	71.57
4690	-333.3	-202.91	41.3	1.8	-0.2	2.60	71.98
4790	-304.6	-188.51	41.3	2.4	-0.2	3.37	72.20
4890	-286.9	-175.80	43.1	2.9	-0.3	3.94	72.52
4990	-274.2	-165.46	50.6	3.4	-0.4	4.37	72.57
5090	-261.3	-158.24	50.6	3.8	0.2	4.76	72.55
5190	-250.7	-151.07	52.5	4.1	5.1	5.13	72.84
5240	-246.0	-145.60	56.3	4.3	20.3	5.31	73.19
5290	-241.1	-140.28	58.1	4.5	44.3	5.45	73.66
5390	-232.2	-131.69	60.0	4.5	55.0	5.46	74.77
5460	-226.6	-126.28	65.6	4.4	53.3	5.41	74.88
	INTERNAL LINE TEMP	TA SKIN TEMP	INTERNAL LEAKAGE	INTERNAL LEAKAGE	INTERNAL LEAKAGE	OUTLET LINE PRESSURE	

G. LPV LH₂ Flow and Leak Test #4

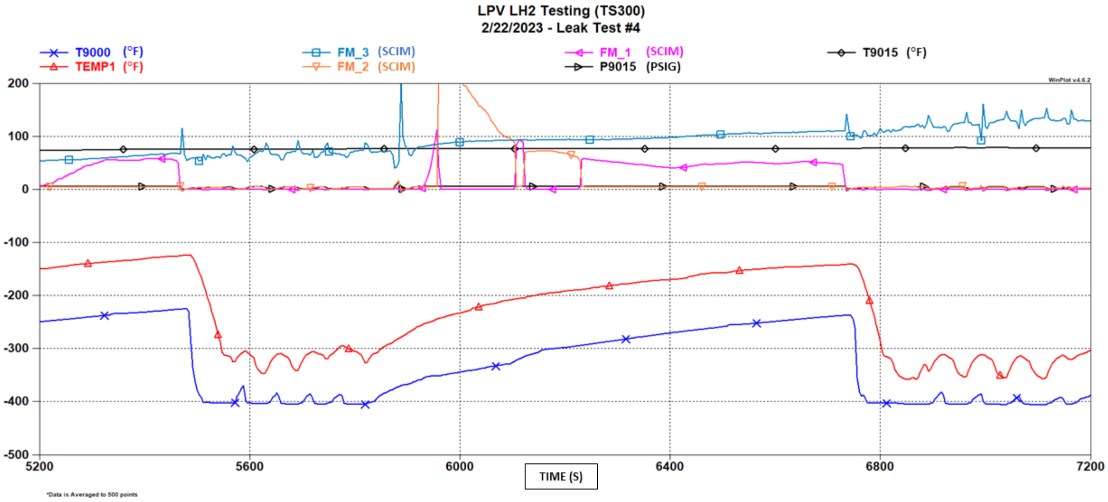
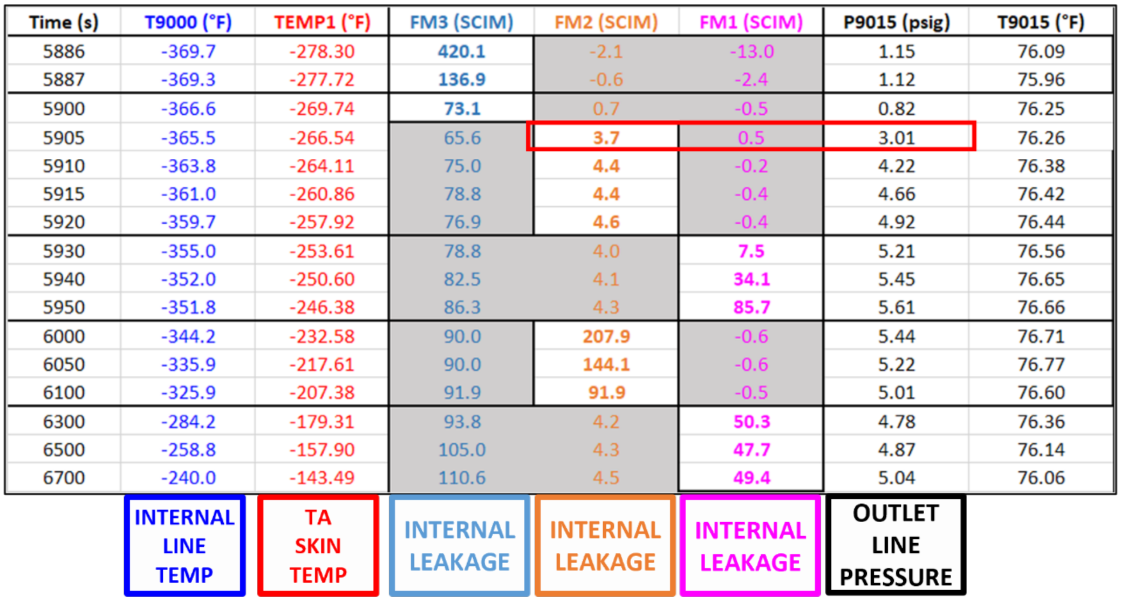


Fig. 50: LPV Flow and Leak Test #4

For LPV Leak Test and Measurement #4, a "short drain" process was performed, quickly closing ROV-915 in an attempt to retain cryogenic temperatures for as long as possible. As with the LLIV, post-test analysis revealed a stronger correlation with outlet line pressure (P9015) than temperature, although the increasing zero-offset of FM3 and FM2 made this correlation more difficult to see. Further complicating observations was the prompt return of elevated line pressures. Despite seeing the outlet line pressure drop to 0.82 psig by a time value of 5900 seconds, it jumped back up to 4.92 psig within 20 seconds (as seen in Table 30). It should be noted that this table has been separated by horizontal lines that indicate a change in time step.

This rapid pressure increase occurred 10 to 20 times faster than in Measurements #1 through 3, and can likely be attributed to a larger volume of hydrogen boiling off, both from the different drain process used, as well as the larger size of the test article. During this time period, the leakage rates measured were at relatively low levels (approximately 4 SCIM), but as P9015 reached 5 psig, the rate of internal leakage began to accelerate. As such, it is believed that the most accurate value for internal leakage is found at the local minimum for outlet pressure and the active flowmeter. In the case of LPV Leak Measurement #4, this value was 3.7 SCIM, occurring at a time value of approximately 5905s.

Table 30: LPV LH₂ Leak Measurement #4 (5886s)



Time (s)	T9000 (°F)	TEMP1 (°F)	FM3 (SCIM)	FM2 (SCIM)	FM1 (SCIM)	P9015 (psig)	T9015 (°F)
5886	-369.7	-278.30	**420.1**	-2.1	-13.0	1.15	76.09
5887	-369.3	-277.72	**136.9**	-0.6	-2.4	1.12	75.96
5900	-366.6	-269.74	**73.1**	0.7	-0.5	0.82	76.25
5905	-365.5	-266.54	65.6	**3.7**	0.5	3.01	76.26
5910	-363.8	-264.11	75.0	**4.4**	-0.2	4.22	76.38
5915	-361.0	-260.86	78.8	**4.4**	-0.4	4.66	76.42
5920	-359.7	-257.92	76.9	**4.6**	-0.4	4.92	76.44
5930	-355.0	-253.61	78.8	4.0	**7.5**	5.21	76.56
5940	-352.0	-250.60	82.5	4.1	**34.1**	5.45	76.65
5950	-351.8	-246.38	86.3	4.3	**85.7**	5.61	76.66
6000	-344.2	-232.58	90.0	**207.9**	-0.6	5.44	76.71
6050	-335.9	-217.61	90.0	**144.1**	-0.6	5.22	76.77
6100	-325.9	-207.38	91.9	**91.9**	-0.5	5.01	76.60
6300	-284.2	-179.31	93.8	4.2	**50.3**	4.78	76.36
6500	-258.8	-157.90	105.0	4.3	**47.7**	4.87	76.14
6700	-240.0	-143.49	110.6	4.5	**49.4**	5.04	76.06
	INTERNAL LINE TEMP	**TA SKIN TEMP**	**INTERNAL LEAKAGE**	**INTERNAL LEAKAGE**	**INTERNAL LEAKAGE**	**OUTLET LINE PRESSURE**	

H. LPV LH_2 Flow and Leak Test #5

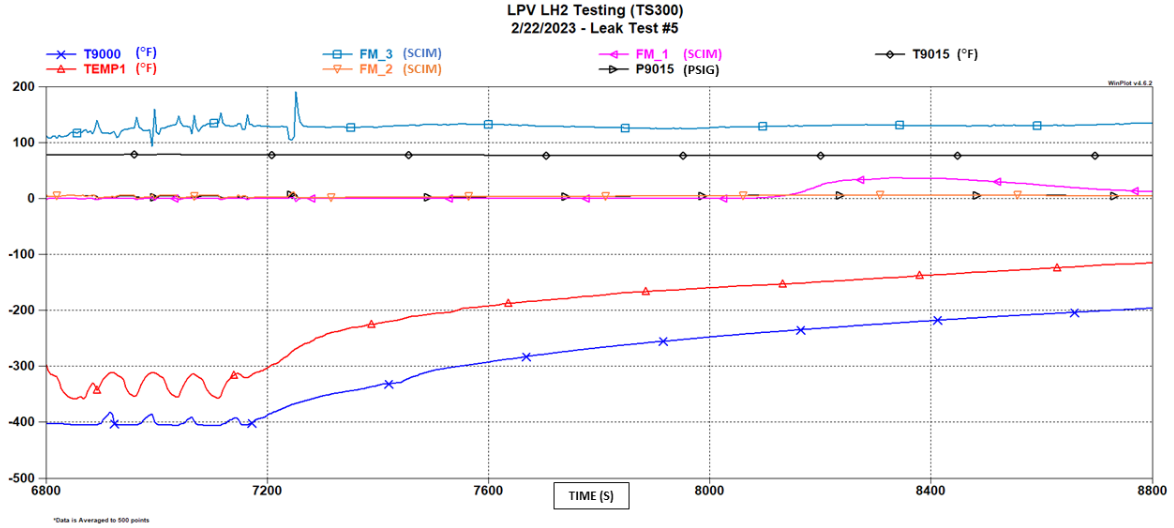
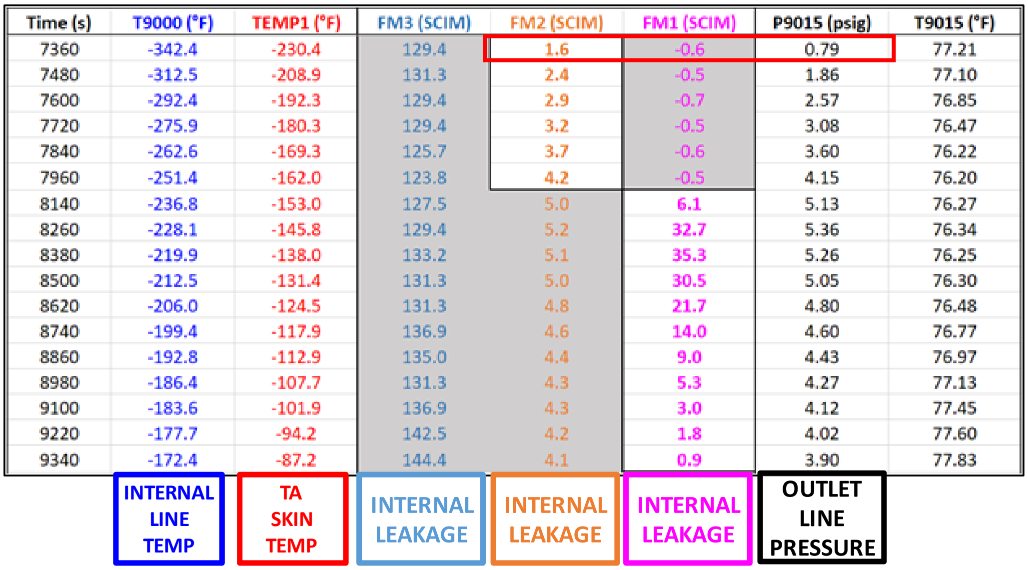


Fig. 51: LPV Flow and Leak Test #5

For LPV Leak Test and Measurement #5, ROV-915 was again allowed to remain open (a “full drain”) in order to remove more hydrogen from the line (and reduce pressure) for leak measurements. This quickly resulted in a local minimum for outlet pressure and the active flow meter. As shown in Table 31, this event occurred at an approximate time value of 7360 seconds, with outlet line pressure (P9015) at 0.79 psig, internal line temperature (T9000) at -342.4°F and test article surface temperature (TEMP1) at -230.4°F.

Internal leakage continued to climb as outlet line pressure approached the 5 psig cracking pressure of the check valve. Although approaching or exceeding the check valve cracking pressure can inflate the measured leakage value, it is more likely that the increased leakage observed was caused by an increase in backpressure, leading to a smaller net sealing force across the poppet and seat. As such, it is believed that the most accurate value for internal leakage is found at the local minimum for outlet pressure and the active flowmeter. In the case of LPV Leak Measurement #5, this value was 1.6 SCIM (with a possible alternative option of 0.9 SCIM occurring at 9340 seconds).

Table 31: LPV LH_2 Leak Measurement #5 (7360s)



Time (s)	T9000 (°F)	TEMP1 (°F)	FM3 (SCIM)	FM2 (SCIM)	FM1 (SCIM)	P9015 (psig)	T9015 (°F)
7360	-342.4	-230.4	129.4	1.6	-0.6	0.79	77.21
7480	-312.5	-208.9	131.3	2.4	-0.5	1.86	77.10
7600	-292.4	-192.3	129.4	2.9	-0.7	2.57	76.85
7720	-275.9	-180.3	129.4	3.2	-0.5	3.08	76.47
7840	-262.6	-169.3	125.7	3.7	-0.6	3.60	76.22
7960	-251.4	-162.0	123.8	4.2	-0.5	4.15	76.20
8140	-236.8	-153.0	127.5	5.0	6.1	5.13	76.27
8260	-228.1	-145.8	129.4	5.2	32.7	5.36	76.34
8380	-219.9	-138.0	133.2	5.1	35.3	5.26	76.25
8500	-212.5	-131.4	131.3	5.0	30.5	5.05	76.30
8620	-206.0	-124.5	131.3	4.8	21.7	4.80	76.48
8740	-199.4	-117.9	136.9	4.6	14.0	4.60	76.77
8860	-192.8	-112.9	135.0	4.4	9.0	4.43	76.97
8980	-186.4	-107.7	131.3	4.3	5.3	4.27	77.13
9100	-183.6	-101.9	136.9	4.3	3.0	4.12	77.45
9220	-177.7	-94.2	142.5	4.2	1.8	4.02	77.60
9340	-172.4	-87.2	144.4	4.1	0.9	3.90	77.83
	INTERNAL LINE TEMP	TA SKIN TEMP	INTERNAL LEAKAGE	INTERNAL LEAKAGE	INTERNAL LEAKAGE	OUTLET LINE PRESSURE	

I. Summary of LPV LH_2 Flow and Leak Test Results

A summary of results from LPV LH_2 testing is shown in Table 32. A few important points are listed below:

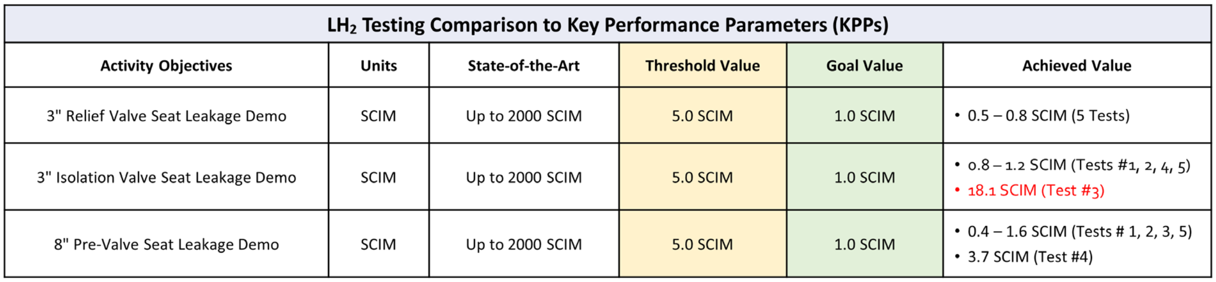
1) Outlet line pressure (or backpressure) from the check valve likely affected the measured internal leakage rates, primarily acting to inflate the values recorded.
2) The most accurate internal leakage rates recorded for each test are believed to have occurred at (or shortly after) the local minimums for outlet pressure and the active flowmeter. These are the "Leakage" values shown in the table below, and occurred before the outlet line pressure began to approach the check valve cracking pressure.
3) Internal leakage rates recorded at or above 5 psig were likely exaggerated by additional flow introduced by the check valve cracking.
4) Internal leakage rates observed on the "Short Drain" test (LT#4) were further exaggerated by a significant increase in hydrogen boiloff versus what was seen on "Full Drain" tests.
5) Internal leakage rates measured are likely the cumulative sum of the true leakage rate, hydrogen boiloff effects, and shifts in flowmeter zero-offsets due to temperature.

Table 32: LPV LH_2 Summary

	Leakage	Outlet Pressure	Notes
LT #1	≤ 0.4 SCIM	1.12 psig (rising)	"Full Drain".
LT #2	≤ 1.2 SCIM	1.72 psig (rising)	"Full Drain".
LT #3	≤0.6 SCIM	0.69 psig (rising)	"Full Drain".
LT #4	≤ 3.7 SCIM	3.01 psig (rising)	"Short Drain"
LT #5	≤ 1.6 SCIM	0.79 psig (rising)	"Full Drain".

VIII. Conclusion

The self-aligning poppet and seat design showed internal leakage rates that met or exceeded the activity Key Performance Parameters (KPPs) in all LN_2 measurements, and in 14 out of 15 LH_2 measurements, as shown in Fig. 52. The single instance that exceeded the threshold value was likely due to a “Short Drain” procedure which was ended too soon, as described in LLIV LH_2 Leak Test #3.



LH_2 Testing Comparison to Key Performance Parameters (KPPs)					
Activity Objectives	**Units**	**State-of-the-Art**	**Threshold Value**	**Goal Value**	**Achieved Value**
3" Relief Valve Seat Leakage Demo	SCIM	Up to 2000 SCIM	5.0 SCIM	1.0 SCIM	• 0.5 – 0.8 SCIM (5 Tests)
3" Isolation Valve Seat Leakage Demo	SCIM	Up to 2000 SCIM	5.0 SCIM	1.0 SCIM	• 0.8 – 1.2 SCIM (Tests #1, 2, 4, 5) • 18.1 SCIM (Test #3)
8" Pre-Valve Seat Leakage Demo	SCIM	Up to 2000 SCIM	5.0 SCIM	1.0 SCIM	• 0.4 – 1.6 SCIM (Tests # 1, 2, 3, 5) • 3.7 SCIM (Test #4)

Fig. 52: Key Performance Parameters

One potential opportunity for improvement includes improving the limited measurement techniques to accurately assess the temperature and phase of hydrogen within the test article. Potential methods to address this issue include the implementing liquid baths or the utilizing a vacuum chamber. These improvements would provide better control and measurement capabilities, enabling more precise assessment of hydrogen temperature and phase while testing. Another opportunity for improvement includes elimination of the check valve used to prevent cryopumping, which had a negative impact on determining the true internal leakage rate accurately. Alternative measures to overcome these limitations may include incorporating thermal insulation to minimize cryopumping effects, redesigning flow paths to optimize gas flow and reduce leakage, or incorporating adjustable flow restrictions to improve control over gas flow rates. Implementing these improvements will increase accuracy and reliability in measuring internal leakage rates, facilitating a more comprehensive evaluation of test results.

Challenges continue to exist for future long-duration missions that seek to utilize cryogenic propellants. Although currently-available valve technology could allow for an unacceptable amount of propellant loss, ER14’s self-aligning seat-and-poppet design may help mitigate the risk of propellant loss due to internal leakage. The test valves utilizing this technology have shown promising results in both LN_2 and LH_2 testing, and the design information will be made available to potential industry partners in Fiscal Year (FY) 2024.

Acknowledgments

This work was funded by the Cryogenic Fluid Management (CFM) Portfolio Project under the Technology Demonstration Missions (TDM) at NASA.

References

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