Heritage to Flight; The Test Program that Brought an Inflation System Back to Life for the Low Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID)

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Following the success of the Inflatable Reentry Vehicle Experiment-3 (IRVE-3) project, the Terrestrial Hypersonic Inflatable Aerodynamic Decelerator (HIAD) Orbital Reentry (THOR) project was stood up with a "built to print" Inflation System utilizing the IRVE-3 flight spares. When THOR was canceled, this Inflation System had already been tested and assembled, ready for use. Thus, when the Low Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID) was spun up, the THOR system seemed like a good candidate to salvage flight ready hardware. There were, however, some key differences in the IRVE/THOR system and the LOFTID one. LOFTID's HIAD was two times the size of IRVE for starters and would require much higher flows to accommodate inflating such an article within a specific timeframe. With new requirements and a tight schedule, the LOFTID Inflation team set to work to verify flight readiness under LOFTID conditions and eliminate the need to requalify new hardware. LOFTID, utilizing an Inflation System built primarily hardware from IRVE-3 spares, successfully flew in November of 2022. This paper will outline the mission differences, the test campaign used to prepare LOFTID's Inflation System for flight, and some lessons learned in repurposing older hardware.

I. Introduction

On November 10th, 2022, the Low Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID) mission launched as a secondary payload on a United Launch Alliance Atlas V launch vehicle from Vandenberg Space Force Base (VSFB). With a successful orbital reentry and recovery of the largest blunt body aeroshell ever flown, this technology demonstration mission advanced the capability and value of the Hypersonic Inflatable Aerodynamic Decelerator (HIAD).

But it did not do such on its own. LOFTID was built on the shoulders of former HIAD suborbital flights. Specifically for this paper, the Inflatable Reentry Vehicle Experiment, or IRVE, missions. In planning for the LOFITD mission, the team opted to repurpose IRVE hardware to save schedule and funding. However, key differences between the flight missions made a simple one for one swap impossible. This paper will discuss the system differences, the test campaign used to prepare LOFTID's Inflation System for flight, and lessons learned throughout.

II. Background

A HIAD is a deployable, inflatable aeroshell that functions as both a heatshield and a decelerator. The technology provides an effective, space-saving, and mass-saving alternative to conventional rigid aeroshells. While the rigid aeroshells are size limited to the diameter of the launch vehicle's payload fairing, and thus limiting the size of payload it can deliver to a planetary surface, a deployable aeroshell can be stowed and then inflated to a much larger diameter. This larger diameter creates a larger drag area and provides for a more rapid deceleration in the upper reaches of the atmosphere enabling the landing of heavier payloads at higher altitudes.

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The HIAD is primarily composed of two elements: the Inflatable Structure, or IS, a stacked toroid structure that deploys and forms the stable aeroshell; and the Flexible Thermal Protection System, or FTPS, a layered heat shield system insulating the IS and payload from hypersonic atmospheric reentry heating. HIAD enables numerous return applications covering everything from low-Earth orbit return to International Space Station (ISS) down-mass and from Mars landings to launch vehicle assets recovery.

In 2009, IRVE-II performed the first fully successful HIAD flight test; inflating a 3m diameter cone prior to atmospheric entry and demonstrating that the inflatable aeroshell would remain inflated and stable through reentry and decent. IRVE-3 launched a redesigned Reentry Vehicle (RV) in 2012 with the same general vehicle configuration as IRVE-II, but with an improved Inflatable Structure (IS) and Flexible Thermal Protection System (FTPS). The next follow-on mission was to be the Terrestrial HIAD Orbital Reentry (THOR) in 2016. THOR planned to use an IRVE-3 Build-to-Print centerbody with a duplicate inflation system, Center of Gravity (CG) offset system, avionics, and Attitude Control System (ACS). The THOR project, despite having already built the centerbody and duplicate systems from IRVE-3 flight spares, was cancelled following the loss of the Cygnus Antares Orb-3 mission. When LOFTID was stood up, the plan was to utilize the as-built Inflation System from THOR. Using IRVE-3's Flight Spare components allowed the team to claim flight heritage, thereby saving schedule and funding by avoiding a redesign and negating numerous qualifying tests.

At its most basic level, the Inflation System is required to inflate the HIAD within an allotted timeframe per the mission's trajectory while preventing the HIAD from over pressurizing. The system also must keep the HIAD inflated to maintain the Aeroshell's stability throughout the mission. LOFTID added an additional requirement of the system to vent off any remaining gas in the inflation tanks after the mission was completed, aka when the RV reached Mach 0.7, for a safe recovery.

The Inflation System for both missions held inert Gaseous Nitrogen (GN2) in storage tanks. At the start of the inflation sequence, the system would command open a valve, the Mass Flow Control Valve (MFCV), which sent gas from the tanks, through a Pressure Regulator (PR), past the MFCV and finally into the HIAD as a regulated, smooth flow of GN2. As the HIAD approached its set pressure, the Inflation System would incrementally close the MFCV to prevent over pressurization. The system also monitored the HIAD's pressure throughout the mission and would open the MFCV to provide make up gas as needed. Both missions also contained a suite of instrumentation used in ground-based testing to confirm the system's functionality and during flight for post processing data. LOFTID's full schematic can be seen in Fig. 1.

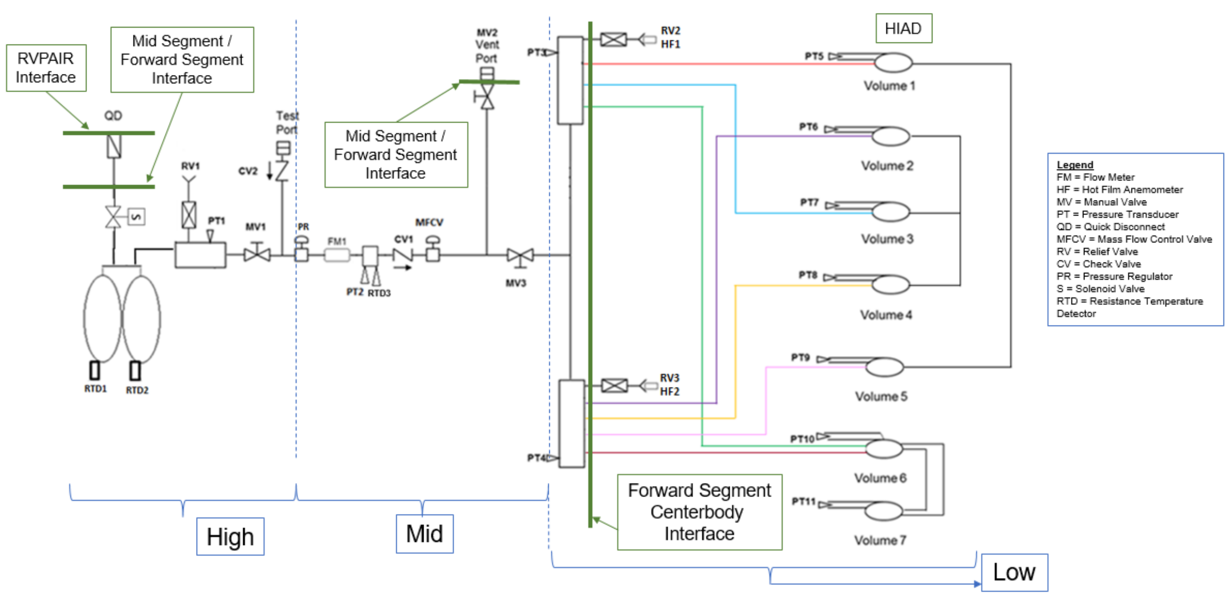

Fig. 1 LOFTID Inflation System Schematic

III. Mission Differences

As mentioned, when LOFTID planned to remove the as-built Inflation System from THOR and place it directly into LOFTID's centerbody, thereby saving schedule and funding. However, a few key differences between missions negated the one-to-one replacement plan. Differences, both physical and operational, necessitated changes for the system's design and components.

A. Physical Mission Differences

The first difference of note is the physical size of the spacecraft. IRVE-3's centerbody was 18" in diameter with a 3m Aeroshell, while LOFTID had a 50" diameter centerbody and a 6m Aeroshell.

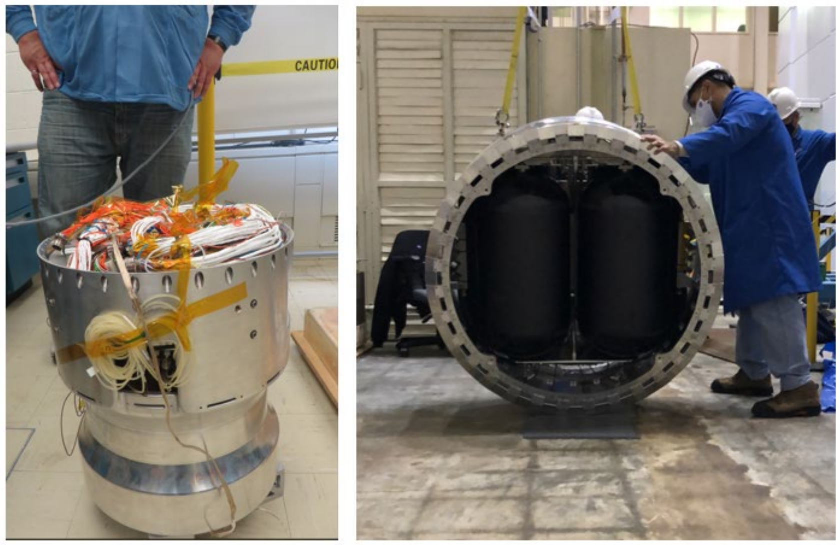

Fig. 2 IRVE-3 Centerbody (Left) vs LOFTID Centerbody (Right)

Thus, while IRVE-3's Inflation System easily fit into LOFTID's centerbody, it was not the best use of the space. For example, IRVE-3's centerbody constraint necessitated numerous 90º tube bends that could be rerouted into a more efficient flow path given LOFTID's larger volume. See Fig. 3 and Fig. 4 for updated pneumatics configuration. The plan became to remove all components from the As-Built system and reposition them onto a newly designed pneumatics plate for LOFTID. The team could, therefore, still claim heritage for all components while optimizing the flow path and flight flow performance.

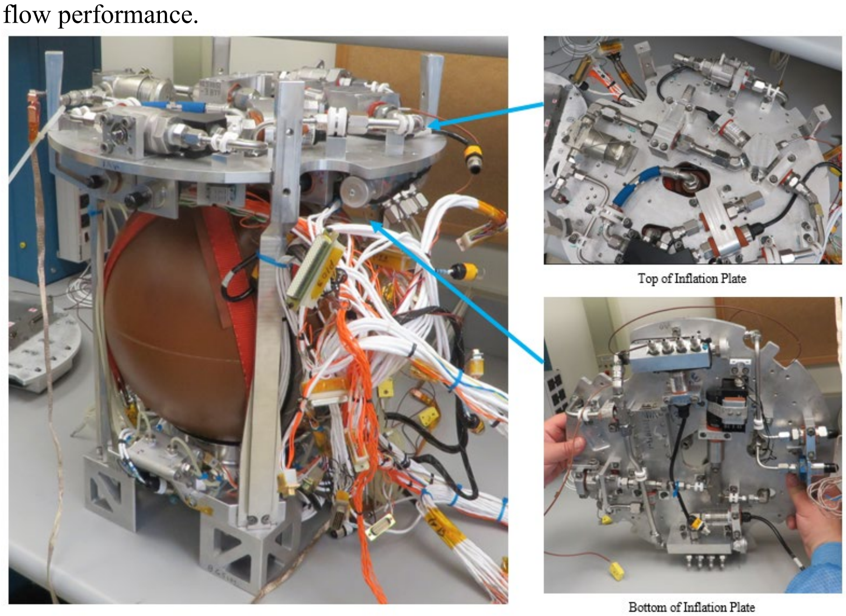

Fig. 3 IRVE-3 Pneumatic Plates

Fig. 4 LOFTID's Updated Pneumatics Plate

As mentioned, LOFTID's mission doubled IRVE-3's 3m Aeroshell, increasing the HIAD build capability to 6m. The IRVE missions were 60º sphere-cone geometries, sharer in both cone angle and nose radius than LOFTID. LOFTID's increase to a 70º geometry permitted this larger diameter HIAD. This change also enabled the technology to demonstrate a "worse case" capability of the IS under drag loading in a Mars-like heating environment. For the Inflation System, this change meant that instead of delivering the amount of GN2 required to fill and maintain a 3m article; it had to do so now for the 6m article.

Such a great quantity of GN2 within the Aeroshell also demanded an increase in gas storage tank size. Thankfully, this is where having a larger volume spacecraft helped and LOFTID's scaled up tanks easily fit in the new centerbody. Where IRVE-3's tank was a Mil-Spec DOT tank capable of carrying 905 cubic inches of GN2, LOFTID contained two Composite Overwrap Pressure Vessels (COPVs), each with a minimum volume of 5,290 in^3. The size difference of the IRVE-3 vs LOFTID tanks can also be seen in Figs. 3 and 4 between IRVE's brown, sphere-shaped tank and LOFTID's dual tanks as black cylinders with spherical ends.

This tank change became the first component switch to no longer hold the IRVE-3 Flight Heritage designation.

B. Operational Mission Differences

While the physical changes to the mission definition caused a redesign of the overall routing of IRVE-3's Build-to-Print Inflation System and an updated gas storage scheme, operational changes required a closer look at each of the pneumatics components selected and used for IRVE.

Trajectory differences between the missions changed the inflation timeline, or amount of time it takes to bring the Aeroshell to its set pressure. Between the larger Aeroshell and updated timeline, the flow rates for LOFTID became about 3.5x higher than the flow rates for IRVE-3. This higher flow rate was the first indicator that the team may not be able to replace only the inflation tanks.

While the storage size increased, both the LOFTID and IRVE-3 tanks held GN2 at the same pressure. Downstream of the tanks, however, the internal pressure needed to increase to provide the appropriate back pressure to maintain this higher flow rate. Both missions employed a spring balanced Pressure Regulator (PR) to respond quickly and accurately to changes in tank pressure. Thus, these PR provided a smooth, consistent GN2 flow, even as the tank pressure decreased. Each PR was mechanically set via testing to provide a set pressure to step down the 3000 psia stored in the tank. For IRVE-3 this set pressure was 150 psia. With higher flow rate needs, LOFTID's PR was set for flight to 375 psia.

With new operational limits in mind, the team took a deep dive into component performance capability to meet LOFTID's needs.

IV. Testing Campaign

C. Component Level Testing

To determine which components were viable for LOFTID's mission, each item was removed from the THOR Centerbody and tested to the new mission parameters. Of note, even if the mission parameters remained the same, the system and all components would have been tested for viability leakage following storage.

LOFTID's mission plan had always been to test the components at a basic level to confirm the soft seats still held against leakage and that each component still operated as expected. With the mission updates, each component now needed to be more fully re-tested for both performance and capability. Of note, wherever a vendor informed the team that the new conditions, specifically higher pressure and flow rates, were not within the specifications of the component, that component was replaced with something as close to the original design as possible.

Happily for the testing campaign, the IRVE-3 sounding rocket flight vibration environments encompassed LOFTID's qualification loads, thus each component was not required to be subjected to additional individual vibration testing. However, LOFTID's centerbody was expected to go through a wider thermal range than experienced on IRVE-3. All components with narrow thermal margins, primarily the system's electronic boxes and MFCV, were sent through individual thermal testing to ensure they would operate as expected throughout the mission.

Outside of Loads and Environmental testing, each component was tested to determine its viability. Both in performance as the soft seals in various items were nearing the end of their lifespan and could create a leak if not verified, and in capability of operating within LOFTID's requirements. Check valve and manual valves were tested to ensure GN2 wouldn't pass through a "closed" valve. Relief Valves were tested for flow and crack pressure set points. Hot Film Anemometers were tested for excitation readings and appropriate positioning on the Relief Valves.

At the timeframe of component level testing in the project, the exact trajectory was unknown. Therefore, the exact timeframe in which the Inflation System had to fill the Aeroshell was unknown. This resulted the most comprehensive testing for the PR and MFCV. Each were subjected to various set points in anticipation of multiple trajectory opportunities. Additionally, GN2 was flown through each component at sea-level-static and vacuum conditions to ensure there would be no surprises throughout the entirety of the mission. Testing at a component level enabled such activities, allowing the team to be flexible and adapt as the mission gained definition. The team did not have to return to the testing phase to determine if updated trajectories were workable as we intimately knew the capabilities of the components.

Ultimately, due to the rigorous component level testing and research, very minor changes allowed the IRVE-3 system to serve for the LOFTID mission. These changes included an updated spring for the PR to allow a higher pressure set point, a blade angle change within the body of the flow meter to allow for higher flow, and an overall increase in part number size for the low-pressure relief valves.

D. Subsystem Level Testing

Once the components had been either verified or replaced the system was assembled and the testing campaign resumed.

LOFTID, as a secondary payload, did not have launch authority and could be required to sit, ready for launch for up to 30 days. As LOFTID's Inflation System was not a welded system, it slowly leaked GN2 through the fittings from the tanks to the pressure boundary of the MFCV. To ensure the system would carry enough GN2 to complete the mission regardless of launch delay, the team calculated an acceptable leak rate and leak checks of the system became one of the most frequent tests performed. The team meticulously applied Snoop compound on each joint, inspecting for the appearance of bubbles any time the system had to be disassembled or modified. This testing allowed the team to have full confidence in the quantity of GN2 stored come launch day.

An additional test frequently performed was the Functional Test during which GN2 was plumbed into the system via a test port and flowed through the system and out a vent port prior to the Aeroshell as the MFCV opened and closed. Such testing enabled the team to verify the system was performing as expected following any shipping, centerbody assembly work, or higher-level testing without putting cycles on the Inflation Tanks or inflating the Aeroshell. If pressures, flow rates, and temperatures all remained in the expected range during these tests; the Inflation System was deemed good to go and did not require further inspection.

While the various components did not require individual vibration testing, the full system was put through Proto-Flight vibration levels. This was performed with the Inflation System installed in the Engineering Development Unit (EDU) Forward Segment and Mid Segment centerbody so the system could accurately experience flight loading. The test was completed at Goddard Space Flight Center (GSFC)'s vibration lab, the configuration of which can be seen in Fig. 5.

During the test, the team discovered a joint that had been missed in analysis and broke off when put under loading, thus requiring re-design. Discovering such an update at subsystem level testing enabled the team to modify the hardware on-site and continue testing, saving time and funding. Had the team not performed this (and other subsystem) test-as-you-fly type testing, the disassembly required to get to the joint during the full RV vibe test would have been disastrous to the project.

Fig. 5 Inflation System Vibe Test Configuration

The most visibly interesting subsystem level tests were the Inflatable Volume Tori Simulator (IVTS) tests. Most Inflation System tests are very loud, but little happens visually. IVTS testing was the first time the system was integrated with a stacked, mock-HIAD, or IVTS. The system inflated the IVTS under nominal and off-nominal conditions, examining how the system responded if an inflation or gang line came detached and testing the limits of the controller. It was also the first time the system confirmed the inflation timeline as predicted from analysis, determine which Tori would come to pressure first and which came last, and enable the team to visualize the flight mission.

Fig. 6 IVTS Pre and Post Inflation Test

E. Full System Testing

Once the components had been verified and assembled into a system, and the Inflation System had been verified via testing as a subsystem, the subsystems were integrated to form the LOFTID spacecraft. The full system level test was the Complete System Test (CST) where LOFTID was installed into once of the vacuum spheres at Langley Research Center and the full flight sequence was performed. Due to the meticulous testing campaign leading to LOFTID's integration, the test was seamless, providing the team with the last visual of the inflated HIAD prior to launch. Eventually, LOFTID was shipped to VSFB where the Inflation System underwent yet another post-ship Functional Test to ensure there would be no surprises on launch day. Finally, the tanks were topped off to the required pressure determined from the previous subsystem leak testing, and the rocket fairing was closed around our payload.

V. Inflation System Flight Performance

LOFTID launched from Vandenberg Space Force base on November 10th, 2022. It was inflated, spun up, and released to reenter Earth's atmosphere. It survived the reentry environments, appropriately decelerated the spacecraft, and landed in the Pacific Ocean under a parachute looking almost as pristine as when it launched. It was a picture-perfect performance.

Unfortunately for the Inflation System, a software error caused all but two sensors to not be recorded throughout flight. These sensors were the two Hot Film Anemometers (HFA) designed to indicate when the relief valves opened by recording the temperature differential measured as a change in voltage as the GN2 flowed over the HFA. The relief valves were mounted, one each, on the Fill Manifolds that divided up the flow and sent it, via the flexible fill hoses, into the HIAD. The relief valves were sized to protect the HIAD from over pressurization due to a failure of the MFCV to close and due to heat soak back as the RV reentered Earth's atmosphere.

The real time data retrieved during flight provided only one data point prior to the system's intentional vent. Therefore, while the flight was picture-perfect, there was very little data to confirm the system performed exactly as predicted.

This is where the importance of the meticulous testing campaign undertaken by the Inflation System team paid off. While the HFA sensor does not provide a quantitative measurement, as in X voltage drop measures Y pressure, testing of the sensors enabled the team to recognize where in the profile the relief valves were opening vs closing. Testing profiles of the individual relief valves allowed the team to know the crack pressure, reseat pressure, and flow capacity of the valves. This little bit of flight data combined with testing data confirmed that the relief valves didn't open throughout the vehicle's coast following initial inflation, indicating that the lines were secure and the MFCV closed appropriately. The data sets also confirmed both valves opened to release pressure in the Aeroshell after Max Q, performing the required pressure balance for the Aeroshell.

Ultimately, the testing results, combined with the minimal flight data, enabled the team to confirm that the system provided the required pressure and maintained that pressure all while keeping the Aeroshell within the required pressure limits.

Fig. 7 Aeroshell After Separation (Left) and At Splashdown (Right)

VI. Best Practices and Lessons Learned

Throughout this paper, the importance and benefit of a rigorous testing campaign have been extolled. During the testing campaign, the team learned and recorded items of note both for the components themselves and pneumatic testing in general.

Some of the IRVE-3 flight spare components that had been in storage since the THOR build were stiff to operate. Thus, the project determined that prior to initial use, all new and stored components should be cycled as appropriate prior to obtaining nominal test measurements. For example, the manual ball valves were opened and closed 5-10 time prior to installation in their test set up. This both loosened the ball joint for ease of closure should a test anomaly require it and engaged the internal soft set to confirm its seal during testing. The check valves were intentionally "banged" open a few times within the test set up prior to taking flow measurements to reduce chatter from first usage.

During the first relief valve testing, the internal nuts maintaining the set point backed off as the valve was pushed through its operating range. Therefore, once set points had been established, all nuts were staked to maintain recordable crack pressure. This was noted in procedures and drawings as required moving forward from the initial testing.

Also noted during relief testing was the need to run pressurant through fabricated hardware to confirm there are no internal shavings caught in any cavities. The first non-flight manifold built contained such shavings and, when the relief valve was installed and operated, those shavings destroyed the soft seal leaving the relief valve chattering open even under low pressure. Following this discovery all hoses, tubes, and fabricated components were either "blown out" with shop air if not for flight testing or sent to precision cleaning to ensure no pneumatic seals would be damaged due to particulates.

In the same mindset for cleanliness the project determined three best practices to be followed:

1) Filters were installed upstream of the pressure source when using external pressurant for testing
2) All GN2 used was required to be of MIL-PRF-27401, Grade B (99.99% purified) cleanliness or higher to keep the flight hardware clean.
3) When the system was disassembled for any reason, the fittings were to be wiped down with IPA, short runs of tube to be flushed with IPA as applicable, and any assembly support (i.e., Teflon tape, lubricant, crush washers) be replaced on the fittings. This kept older/chewed up lubricant and tape from breaking free of the fittings and traveling downstream.

One of the challenges with utilizing IRVE-3's flight spare was component lifetime. While the metallic hardware performed as expected, throughout testing there were concerns regarding the soft seals internal to components. And not just the original seals. For example, the pressure regulator was sent back to the vendor for refurbishment prior to use. However, the vendor restored the component with a kit containing an O-Ring at the end of its lifespan. This was not discovered until the PR failed to maintain set pressure during system level testing and had to be replaced. The damaged O-Ring was easily discovered upon disassembly of the PR at Wallops Flight Facility. A resulting lesson learned is for any project using components, especially heritage components, with integrated seal to request lot information from the vendor on all seals. The project can then maintain a record of self-life and cycle counts. Often, such information cannot be provided for older heritage components, therefore it is also recommended that future projects carry the risk of a seal failing and allocate appropriate resources to procure spares and plan for replacements.

VII.Conclusion

The November 2022 LOFTID Launch was a successful demonstration of the HIAD technology. The Inflation System brought back to life from the IRVE-3 flight spares provided a picture-perfect inflation and maintained an appropriate pressure balance within the Tori. Due to a rigorous testing campaign that validated the nominal and off nominal operations of each component, the team had full confidence in the system prior to launch.

Despite the minimal Inflation System flight data captured, the thorough test documentation enabled the team to piece together performance details and conclude that the system met its requirements. Lessons learned and best practices gained throughout the testing campaign affirmed the team's choice to "test as you fly" as often as possible. Component level testing enabled the team to be flexible as mission parameters changed while subsystem testing allowed the team to modify hardware with minimal cost or schedule change to the project. The overall lesson learned from such an experience is that, however tedious it may seem at the time, no test is inconsequential.

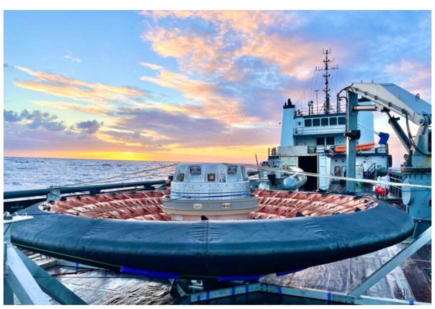

Fig. 8 HIAD Post Flight on the Recovery Ship