Design and Test of the Orion Crew Module Launch Abort System Hatch

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Abstract

The Orion spacecraft is part of NASA's Artemis program to establish a permanent human presence on the lunar surface and further enable future crewed missions to Mars. One of the key safety features of Orion is the Launch Abort System (LAS), which pulls the Orion Crew Module (CM) away in the event of a launch vehicle malfunction. It was necessary to design a LAS Hatch that allows for crew access to the CM during pad operations. This paper describes the background and evolution of the LAS Hatch design, the features used to address the crew safety requirements, the testing challenges in preparation for the Artemis crewed missions, and lessons learned.

Introduction

The Orion Launch Abort System, or LAS, is attached to the top of the Orion Crew Module (CM). It is designed to protect the NASA astronauts if a problem arises during launch by pulling the CM away from a failing rocket. Weighing approximately ~7,250 kg, the LAS can activate within milliseconds to pull the vehicle to safety and position the CM for a safe landing. The LAS is comprised of three solid propellent rocket motors: the abort motor, an attitude control motor, and a jettison motor. The Launch Abort System (LAS) Hatch is a structural / mechanical / pneumatic / electrical component that allows for ingress and egress through the LAS ogive fairing during nominal ground operations and pre-launch activities. It is also required to open quickly in emergency situations on the pad where the crew needs to exit in the event of a spacecraft or launch vehicle malfunction. The deployed LAS Hatch is shown on the spacecraft in Figure 1.

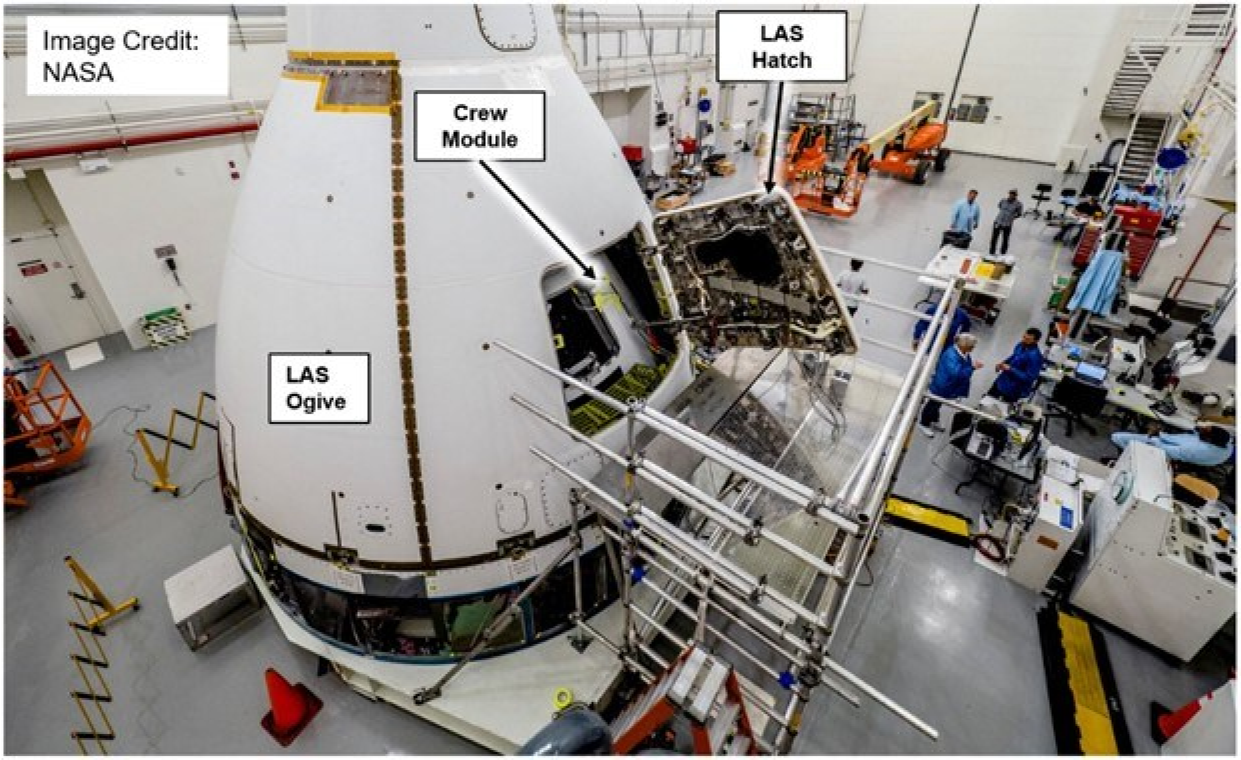

Figure 1: Orion LAS Hatch on the Ascent Abort 2 vehicle

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LAS Hatch Design Details

The LAS Hatch contains the following key components, reference Figure 2:

- Curved aluminum structural panel (conforming to the complex ogive shape of the LAS fairing)
- Window (aligned to the CM Hatch ~0.6 m away)
- 10 pneumatic latches used to compress the perimeter seal and retain the hatch to the LAS structure
- Pneumatic actuation system comprised of solenoid valves, pressure transducers, check valves, batteries, a Composite Overwrapped Pressure Vessel (COPV), and steel tubing
- Perimeter weather and Electromagnetic Interference (EMI)/ Electromagnetic Compatibility (EMC) seal
- Deployment hinges (4-bar linkage design)
- Gate Release Assembly which initiates the emergency egress function (actuated by the opening CM Side Hatch)
- Bumper Assembly which the CM Side Hatch slides along to help open the LAS Hatch
- Tangential and radial hard stops which provide additional structural support
- Strut Assembly (pneumatic strut to help open the LAS Hatch)
- External Handle Assembly for opening the LAS Hatch from the exterior of the vehicle (for both nominal and emergency cases)
- Electrical system comprised of standalone batteries for emergency egress and sensors for crew situational awareness

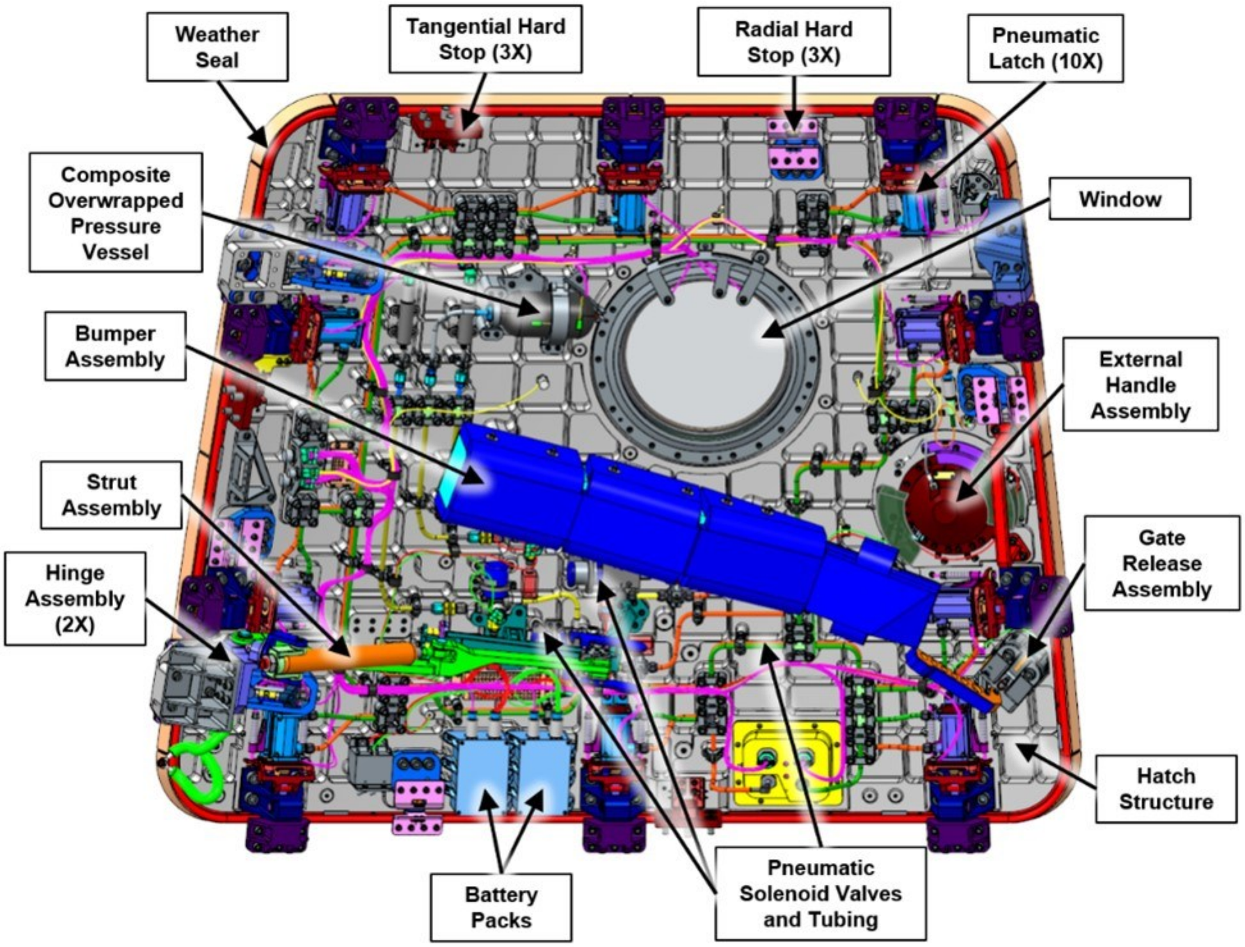

Figure 2: Orion LAS Hatch Overview (Interior View)

Emergency Operation Function

In the event of an emergency on the launch pad where the crew needs to exit the vehicle quickly, there are two scenarios:

1. Initiated by ground operations team: Ground team member pushes a button and turns the External Handle Assembly which actuates the pneumatic system to retract the latches, which then allows the ground team to pull open the hatch (aided by the pneumatic strut assembly)
2. Initiated by the flight crew (Figure 3): An astronaut will open the CM Side Hatch using either the manual gearbox system or an emergency pyro system. The Side Hatch is pushed open with its own pneumatic “counterbalance” strut, which then impacts the Gate Release Assembly on the LAS Hatch. The Gate Release Assembly actuates the LAS Hatch pneumatic system unlatching the latches, which then allows the Side Hatch to push the LAS Hatch open as it slides along the bumper interface.

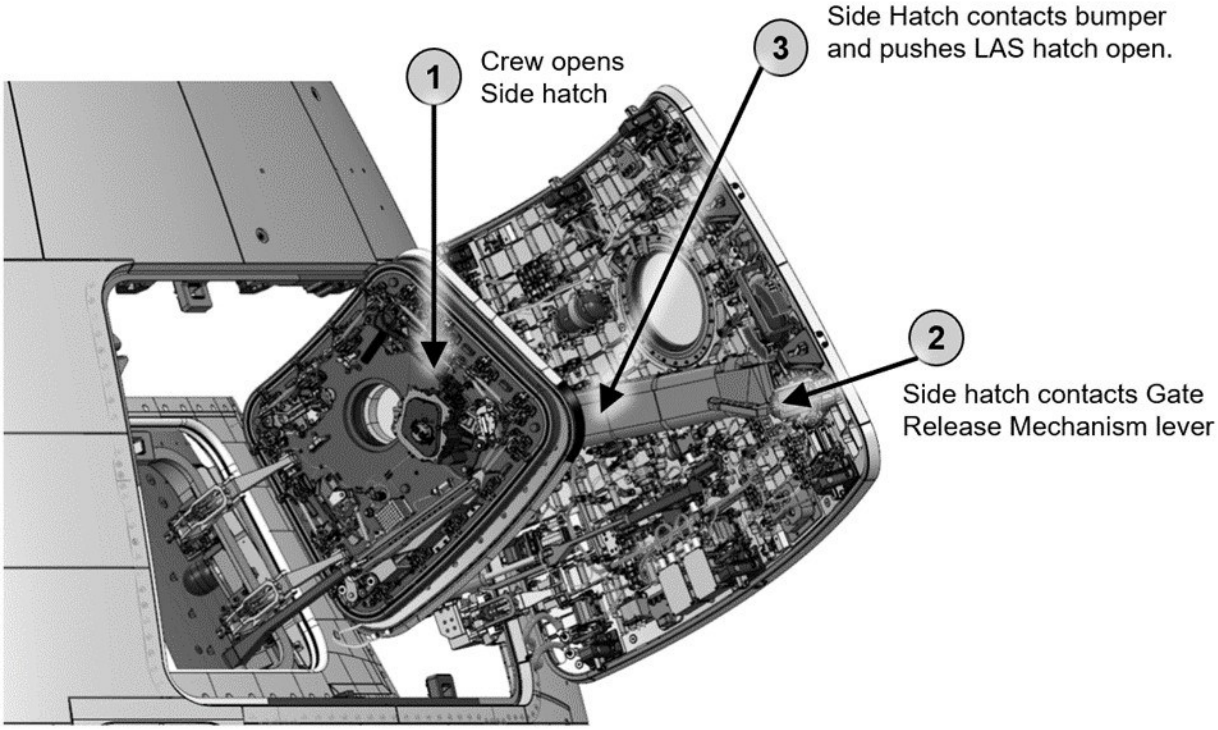

Figure 3: Orion Crew Module Side Hatch and LAS Hatch in Tandem

Design Development

The original pre-Preliminary Design Review (PDR) LAS Hatch design coming into 2014 was a similar design to the Crew Module Side Hatch, a mechanical design with mechanical latches, linkages, bell cranks, gearbox, mechanical release mechanisms, etc. The LAS team was tasked to pursue a less complicated and lower mass design to help reduce the already high mass of the LAS module. The mass of the LAS Hatch had a double impact on the overall LAS module mass (the mass of the hatch itself and the ballast mass opposite the LAS Hatch to maintain a center of gravity along the LAS module axis). The NASA Langley Research Center (LaRC) team developed a pneumatic design concept that simplified the hatch from the mechanical design by replacing the gearbox with an external pressure cart, linkages and bell cranks with pneumatic tubing, latches with pneumatic linear actuators, release mechanisms with electrical release technology, and many other changes. The pneumatic design was originally not looked upon favorably by the mechanisms team. It was a significantly different design from what had been worked and reviewed by the team since the Orion program started in 2006. The advantages of the design were very compelling, but the team would essentially have to restart the design process to implement the significant changes. The team decided to perform a trade study/Assessment of Alternatives (AoA) Analysis with an agreed upon selection criteria (cost, schedule, risk, and mass) that would be weighted and scored using a software tool. The goal was to down select to a single design and then move one design forward to PDR.

NOTE: The original mechanical design used 15 latches (see Figure 4). To make a fair comparison, 4 designs were assessed: 15 latch mechanical baseline, 15 latch pneumatic, 10 latch mechanical, and 10 latch pneumatic. Preliminary analysis indicated that a 10 latch design was a feasible design alternative.

The AoA analysis was performed, and results presented to the Orion community: the 10-latch pneumatic design was the clear winner based on the agreed upon weighted criteria (see Figure 5). The next steps were to mature the details of the design and receive Orion program approval. The Orion community was originally very skeptical of the new pneumatic design, and several boards were needed to move the design towards acceptance. Some changes that were implemented were: Changing from pyro valves to solenoid valves for easier emergency egress turnaround, adding multiple strings of solenoid valves for redundancy (safety), adding pneumatic system updates to cover for unique scenarios such as failed valves, adding a suite of sensors to monitor the pneumatic system/latches/batteries (to provide situational awareness to the ground and flight crews), and adding batteries on the LAS Hatch directly for the case where the vehicle loses power. All of these changes were implemented, and the design approved.

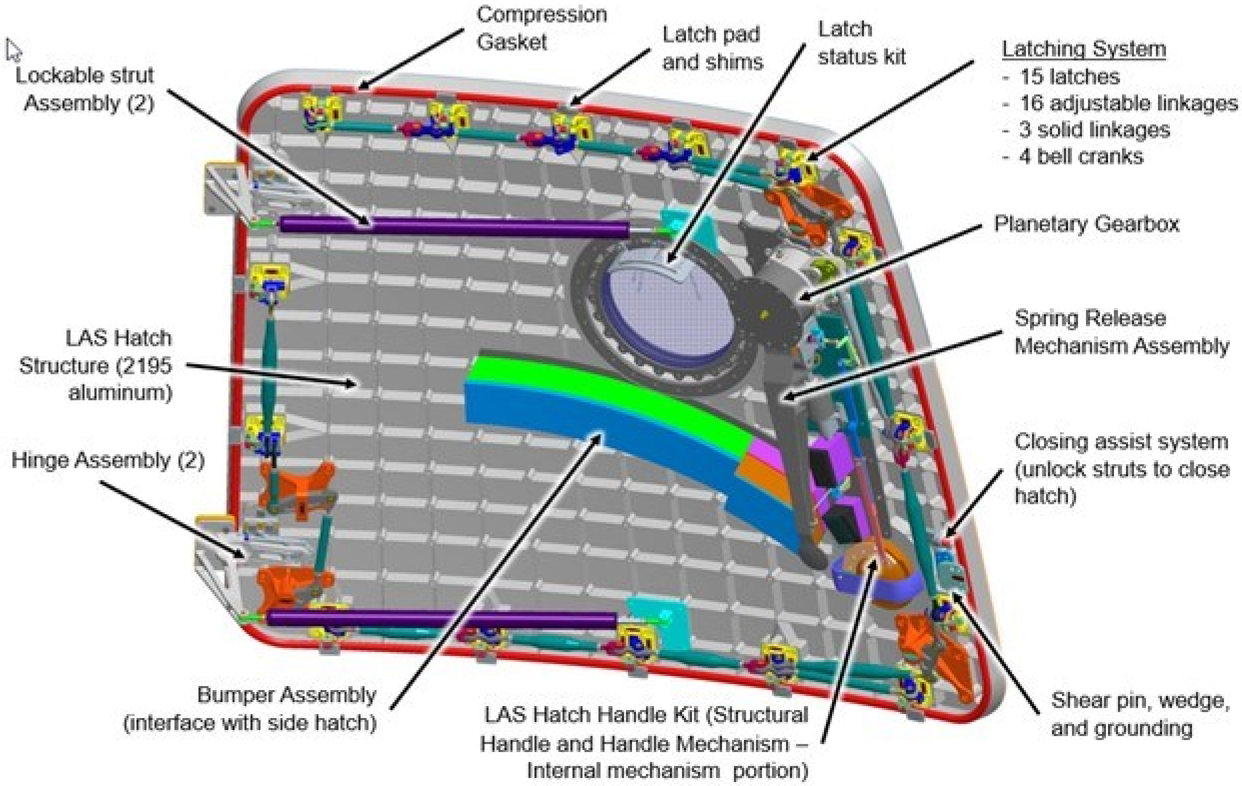

Figure 4: 15 Latch Mechanical LAS Hatch Baseline 2014

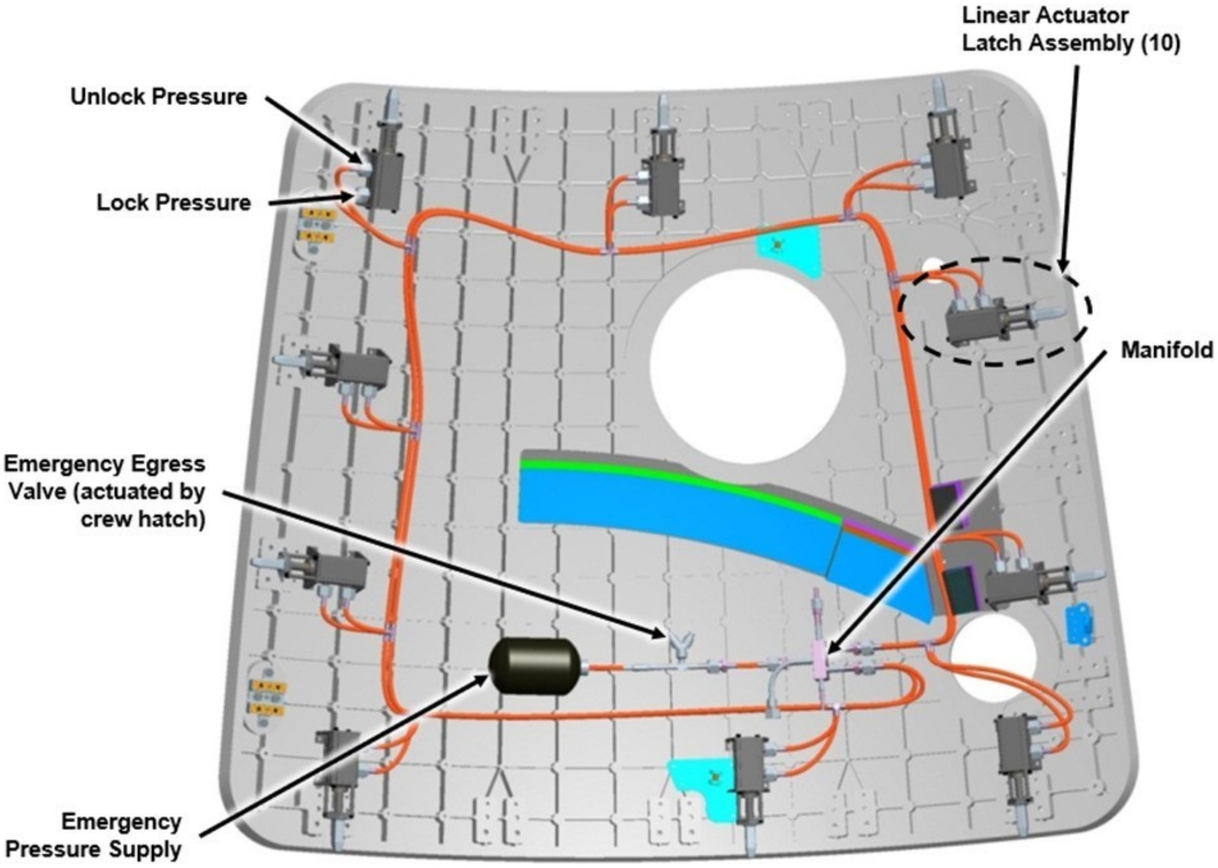

Figure 5: 10 Latch Pneumatic LAS Hatch Concept

Other design trade studies were completed such as:

- Use of venting valves to vent COPV after nominal launch to prevent inadvertent unlatching: Trade resulted in the use of two 2-way valves in series. Venting valves proved too difficult to control for launch sequence.
- Burst disks on closed latch volume: Trade resulted in leaving latch volume open to atmosphere.
- Multiple iterations of the sensor suite: Sensor suite optimized to provide ground and flight crew telemetry within channel allocations.
- Use of 3-way and 2-way solenoid valves: 3-way valve placed in series after the 2-way valve allows any leakage passing thru the 2-way and 3-way valve to vent thru the 3-way venting port. This ensures pressure does not enter unlatch volume.

  Addition of check valves: To prevent leakage into unlatch volume past the 3-way valve and to prevent pressure dump out of a failed to open 3-way valve in one of the valve Strings.
- Approval for adding fully functional LAS Hatch on the Ascent Abort 2 test.

Refer to Figure 6 for the Latch Pneumatic System.

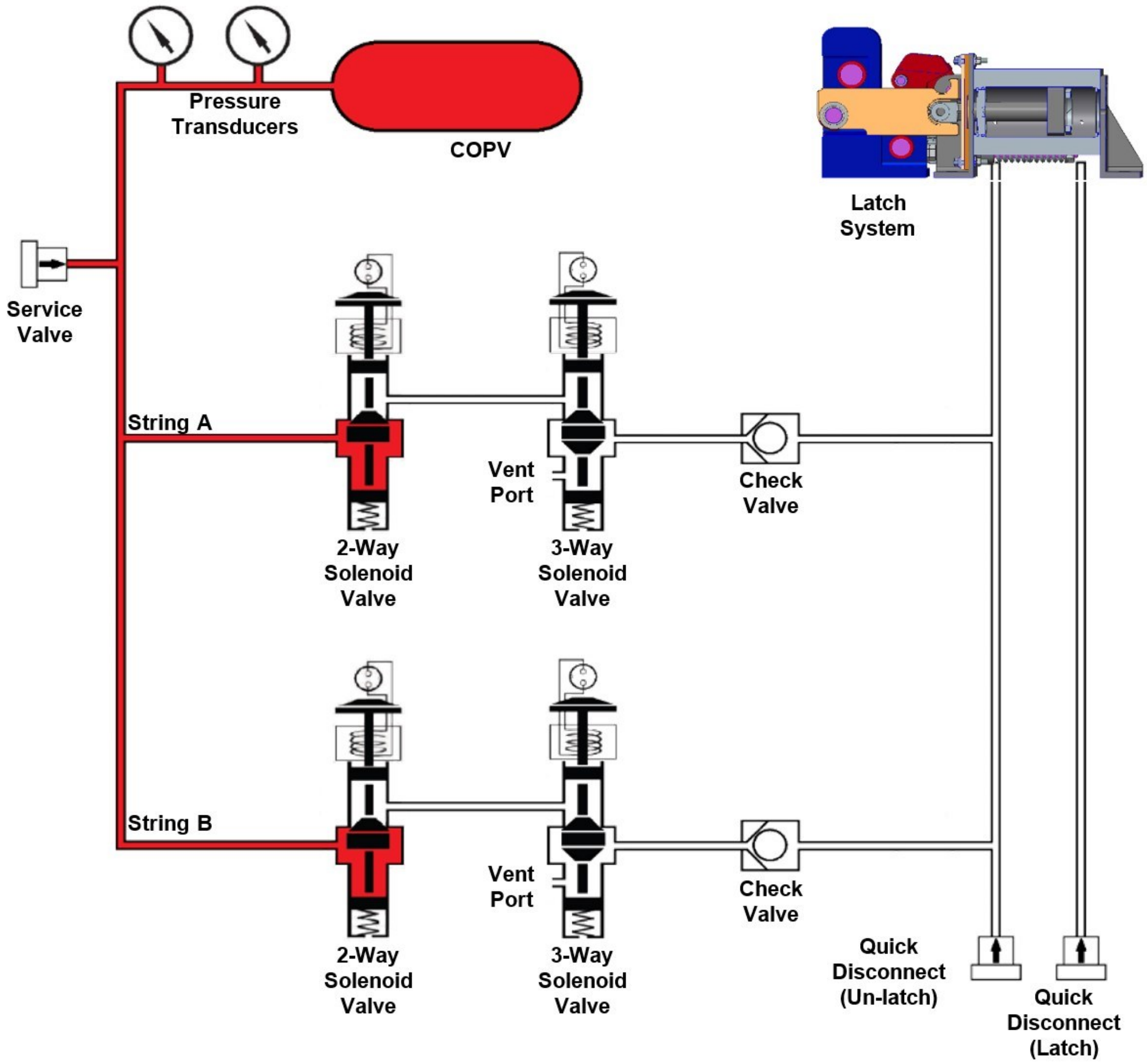

Figure 6: Latch Pneumatic System

Easy 5 (Docan Ltd.) simulating software was used to predict performance of the pneumatic system within the expected environments such as temperature changes. Using the Easy 5 software the simulation was able to predict all 10 pneumatic latch stroke distances and times. Iterations of the analysis consisted of altering tubing size, tubing length, valve configurations, pressure tank size and pressure limits, thermal effects on latch performance including pressure deltas, and predicted performance given various failure modes and redundant systems. Easy 5 simulation software aided in the final design solution of the pneumatic system to meet the latching performance requirements, such as time to unlatch the LAS Hatch in an emergency egress using worst case pressure changes due to thermal deltas and failure modes of redundant systems.

The initial pneumatic latch design used for the trade study with mechanical latches consisted of a pneumatic actuator, latch housing and the latch bolt. The actuator drove the latch bolt thru the housing and into the receiving side of the LAS Hatch frame. Thru multiple design iterations the design evolved to that shown in Figure 7.

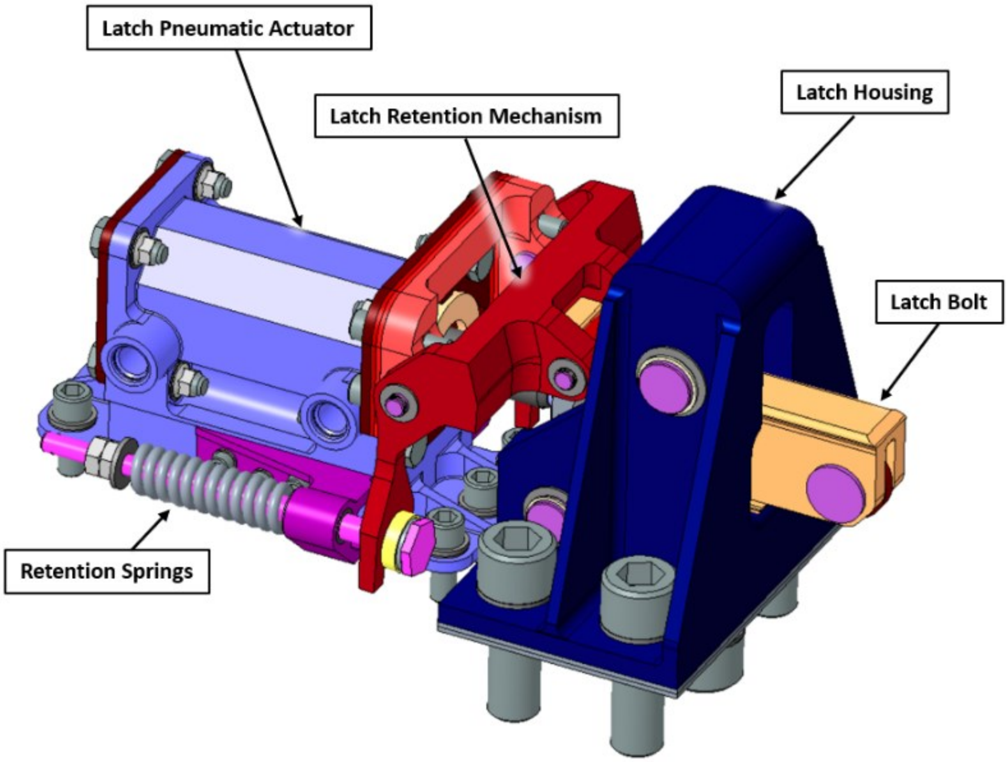

Figure 7: LAS Hatch Latch Mechanism

Due to the extreme acoustic environment created by the LAS rocket, several challenges had to be met including but not limited to:

- Ensuring latches remained latched during abort scenarios and random vibe environment
- Loads induced during abort sequence
- Hatch structure deflecting or "potato chipping" whereas the hatch structure would warp, creating large local deflections between hatch and frame
- Time for latches to unlatch in an emergency egress

The high acoustic levels generated large deflections between the hatch and the frame. Since the hatch is not required to maintain pressure before, during, or after flight (the seal between the hatch and frame is only for latch preload and electrical grounding requirements) the deflections were not a concern in terms of gapping. However, to reduce the overall loads within the hatch structure and reduce bending, the seal preload required would be an unattainable amount due to mass/stiffness. This required the design to have latches that retain the load in both directions. One direction is the hatch pushing outward against the Latch Ramp, compressing the seal further until the hatch bottoms out on frame bumpers (plastic strips along the frame such that the hatch does not contact metal to metal against the frame). The other direction is when the hatch pulls away from the frame. For this direction a receptacle was added on the frame limiting the amount of hatch deflection. Figure 8 shows a cross section of the actuator and latch which outlines the 2 different load paths and how they are resolved within the latch housing. As the latches are engaged the bolt rollers (shown as the red load path in Figure 8) allow the latch to move along the incline of the latch ramp, compressing the hatch seal and serving as the load path within the latch housing for direction 1. For the reverse direction the load path is resolved by hard stops located within the latch housing (shown as the yellow load path in Figure 8).

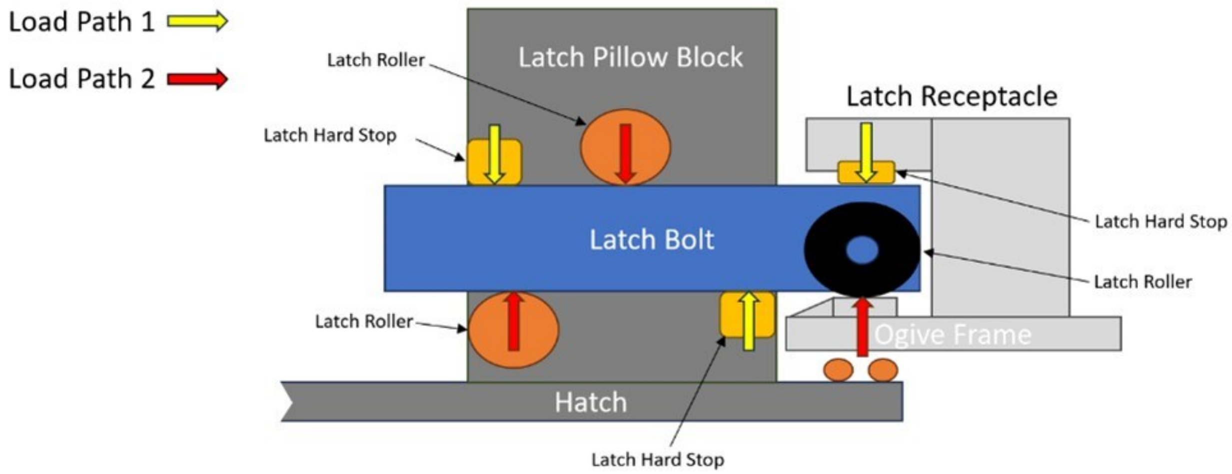

Figure 8: LAS Hatch Latch Mechanism Load Path Diagram

The pneumatic latches also provided a system that was not as affected by hatch structure deflections that a mechanical system would be. Since mechanical latches require linked mechanisms to operate a latch, those links are subject to hatch deflections that may alter latch over center positions, latching positions, as well as preload. The pneumatic latches are not dependent on mechanical links for latching.

The original plan for the linear actuator was to use a vendor supplied item or COTS hardware. The vendor chosen to make the actuators decided to back away from the project due to the environments and challenges of space hardware. This provided an opportunity to design a customized actuator that better suited the hatch interfaces, packaging constraints and performance which ultimately allowed for a much lighter and more efficient design.

The LAS Hatch pneumatic tubing system was designed as a lightweight solution to transfer energy and latch or unlatch the actuators, allowing the hatch to be “locked” or “unlocked”. The tubing system, as seen in Figure 9, can be broken down into four sub-systems: high-pressure weldment, solenoid valve weldment, low-pressure unlatch weldment and low-pressure latch weldment. The pneumatic actuators are connected to the low-pressure latch and unlatch weldments where they can be actuated using a pressure cart on the ground or an emergency supply of nitrogen gas stored within the high-pressure weldment on the hatch. During an emergency, the solenoid valves are energized through the external handle or gate release mechanisms, releasing the nitrogen and back driving the latches.

Within the high-pressure weldment, the bulk of the emergency nitrogen is stored within the COPV (composite overwrapped pressure vessel) tank. This tank is a standard COTS (Commercial Off The Shelf) item (similar to tanks used in paintball guns). It is designed to be leak-before-burst as a safety feature and is attached to the rest of the weldment through a custom fitting. The high-pressure weldment also includes two identical pressure transducers to measure the actual pressure within the weldment. The weldment is filled using a COTS Schrader valve threaded onto a custom manifold.

The high-pressure weldment is connected to the unlatch weldment through two identical solenoid valve weldments in parallel. This allows for redundancy if one of valve strings is stuck close or fails to energize. Each string is connected to an independent battery box which is mounted to the hatch and is decoupled from overall vehicle power. Within each solenoid valve string, there are two valves. The first valve is a 2-way solenoid and the second is a 3-way solenoid. This allows for accidental leakage past the first valve to be vented to atmosphere unless the valve string is intentionally energized. As part of the development test campaign, these valve strings were successfully tested in a partial abort environment where it was confirmed that although there was leakage past the first valve, the second valve prevented gas leaking into the unlatching weldment.

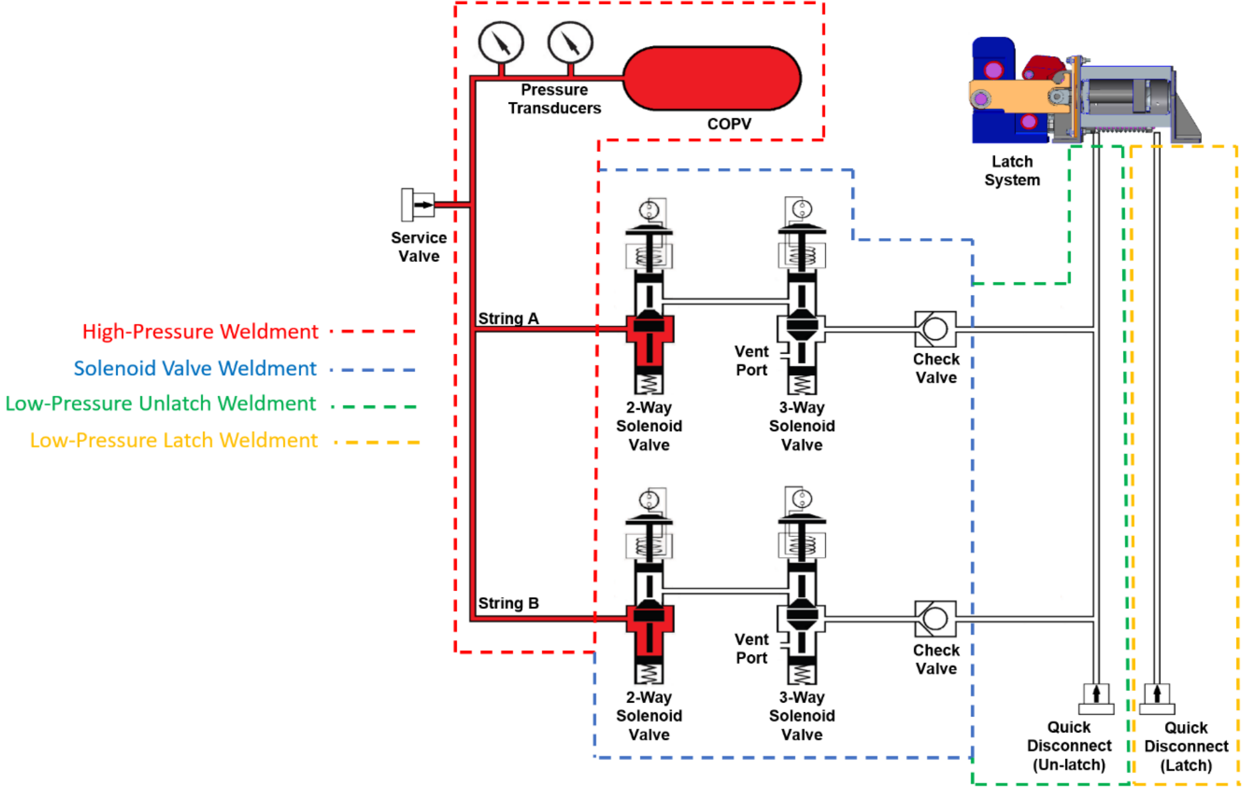

Figure 9: LAS Hatch Pneumatic Tubing System

Originally all the weldments were secured to custom clamps using COTS Teflon cushions and thick, pliable tape. The issue with this design was that it was impossible to simultaneously eliminate gaps while also prohibiting any side load from being induced during assembly. This problem was solved through the development of small injection holes within the clamps to allow for the injection of liquid Room Temperature Vulcanizing Silicone (RTV) between the clamps and tubing.

All tubing weldments are bent, fitted up and welded in-house at Lockheed Martin. To aid the tube assembly on the flight hatch, a weld tool was developed which uses the same flight interfaces but built to tighter tolerances. It also requires the use of the flight actuators which are serialized and installed in the same location on the weld tool as they are on the flight hatch. The weldments are fitted up on this tool prior to any welding and ensures that all the weldments can be assembled onto the flight hatch without issue. Each weldment is proof pressure and leak tested at the individual weldment level and again once they are integrated together on the flight hatch. During this testing it was discovered that the Swagelok fittings are very sensitive to orientation when re-swaging and led to multiple process changes throughout the assembly.

LAS Hatch Development Testing

The LAS Hatch is located directly below a LAS solid propellent rocket motor. When these rocket motors are activated, they provide a substantial acoustic environment for the LAS Hatch. A development unit was made along with LAS ogive test panels to be assembled and tested in NASA's Reverberant Acoustic Test Facility (RATF), see Figure 10. The test facility was not able to achieve the acoustic levels predicted however the data collected was used for model correlation which reduced risk for stress margins.

The EDU LAS Hatch used for the acoustic test at RATF was the same hatch and hardware used for the Ascent Abort-2 test (AA-2) shown in Figure 11.

Figure 10 (Left): EDU LAS Hatch installed into LAS Ogive test assembly at NASA's Reverberant Acoustic Test Facility (RATF)

Figure 11 (Right): Ascent Abort-2 test conducted on July 2nd, 2019, at Cape Canaveral SLC-46 launch site (Photo Credit: NASA/Tony Gray and Kevin O'Connell)

The purpose of the Orion Ascent Abort 2 (AA-2) Test Flight was to demonstrate a full up use of the Orion Launch Abort System (LAS). This test was accomplished by propelling a Crew Module simulator and flight LAS to an altitude of 9,450m, and a speed of roughly 357m/s, on a modified Peacekeeper first stage. During planning for the test, it was decided to fly the LAS Hatch Engineering Development Unit (EDU) as an Artemis I flight like hatch. After the EDU was manufactured, the ongoing analysis showed the vibroacoustic loads continued to increase. These vibroacoustic loads are generated by the LAS Abort Motor firing above the hatch location. Upon review of the AA-2 loads, a decision was made to remove the pneumatic strut from the hatch during final closeout for flight due to negative stress margins on assembly (pneumatic gas strut assembly was later redesigned to handle abort loads). The rest of the EDU remained as designed. After launch, the LAS Hatch went through the flight and abort environments successfully. Upon completion of the test, the LAS descended from altitude and impacted the Atlantic Ocean, and then the seafloor in fifteen feet of water. A recovery crew was dispatched and discovered the LAS Hatch resting on the seafloor being guarded by a nurse shark. With cooperation from Lockheed Martin, NASA was able to recover the LAS Hatch (see Figure 12). The hatch was in good shape and still fully latched. This result provided significant confidence in the design of the LAS Hatch.

Figure 12: Orion AA-2 LAS Hatch Post AA-2 Launch

Tandem Test

To demonstrate the emergency egress capability of the Side and LAS Hatch, a test was performed using a flight like qual Side Hatch and the Artemis II LAS Hatch assembled in a fixture that represents the flight configuration. See Figure 13. After test set up was complete, a series of test cycles were conducted that reflect different emergency scenarios including:

- Side Hatch counterbalance set at different pressures to evaluate individual hatch performances.
- Various openings using different flight and ground crew initiation.
- Employing a flight like equipped (Helmet and Gloves) Artemis II Astronaut that will be responsible for Side Hatch openings to perform various Side Hatch emergency and nominal openings.

Concerns going into the tandem testing revolved around the Side Hatch and LAS Hatch hinge capabilities. The hinges were designed to kinematically open normal to the hatches for a certain distance to minimize shear loading on hatch seals. After this predetermined distance, the hinges would then rotate the hatches as they are pushed outward. Since the hinges were designed with this kinematic motion, they are sensitive to the overall moment generated on the hatch due to the resultant load on each hatch such as counterbalance, gas strut, side hatch load on LAS Hatch during opening, etc. If the moment generated is high enough at certain kinematic positions of the hinges, then the hinges could “bind” or not be allowed to follow thru with the kinematic motion. The kinematic location where the hinges were sensitive to the hatch moment was found to be near the hinge closed position. This is where the kinematic motion of the hinges transitioned from opening normal to the hatch to a motion of hatch translation and rotation. The hinges were fitted with strain gauges during the tandem test to monitor the induced loads within the links of the hinges. During LAS Hatch installation to ogive for Tandem testing it was also found that proper lubrication of the hinges is essential for proper operation. Lubrication on the hinges was initially called out to be applied sparingly to avoid contaminants on the neighboring LAS Hatch window. However, after several cycles of hatch openings the hinges started to bind. After hinge disassembly the hinge pins showed signs of galling. The lubrication notes for hinge assembly as well as other mechanisms was updated to remove the word sparingly as well as specifying exactly where and how much lubrication to apply. The lubrication Braycote 601 was also replaced with Braycote 602. Braycote 602 includes Molybdenum disulfide which is a primary material for reducing or eliminating the possibility of galling.

The Tandem testing performed was successful. It was found that as long the LAS Hatch Gas Strut provided enough force such that the LAS Hatch was pushed outward and past the sensitive kinematic position, then the load within the hinges remained within stress margins.

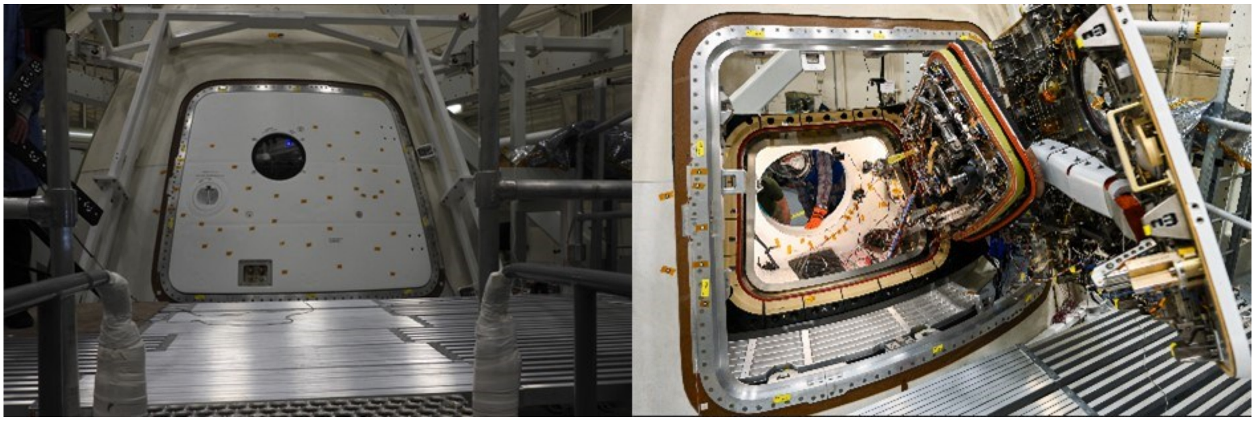

Figure 13: Tandem Testing
(Left Picture – Hatches Closed)
(Right Picture – Hatches Open)

Analysis Approach

The LAS Hatch analysis is performed to verify the numerous human rating requirements developed to ensure crew safety. Those requirements ensure the proper form, fit, and function of the hardware. The hardware is assessed against those requirements throughout the expected lifecycle. The definition of the "expected lifecycle" can be a challenging and iterative activity. In the case of the LAS Hatch, one critical event within the lifecycle is the abort event. This extreme set of environments proved challenging to find a mass optimized design and meet a stringent requirement set.

The design complexity of the LAS Hatch required the development of Finite Element Model (FEM) math models. These FEMs are used to help derive environments and perform margin of safety assessments of failure modes. The FEM is an analytical representation of the structure that is used to predict the response when environments are applied to the model.

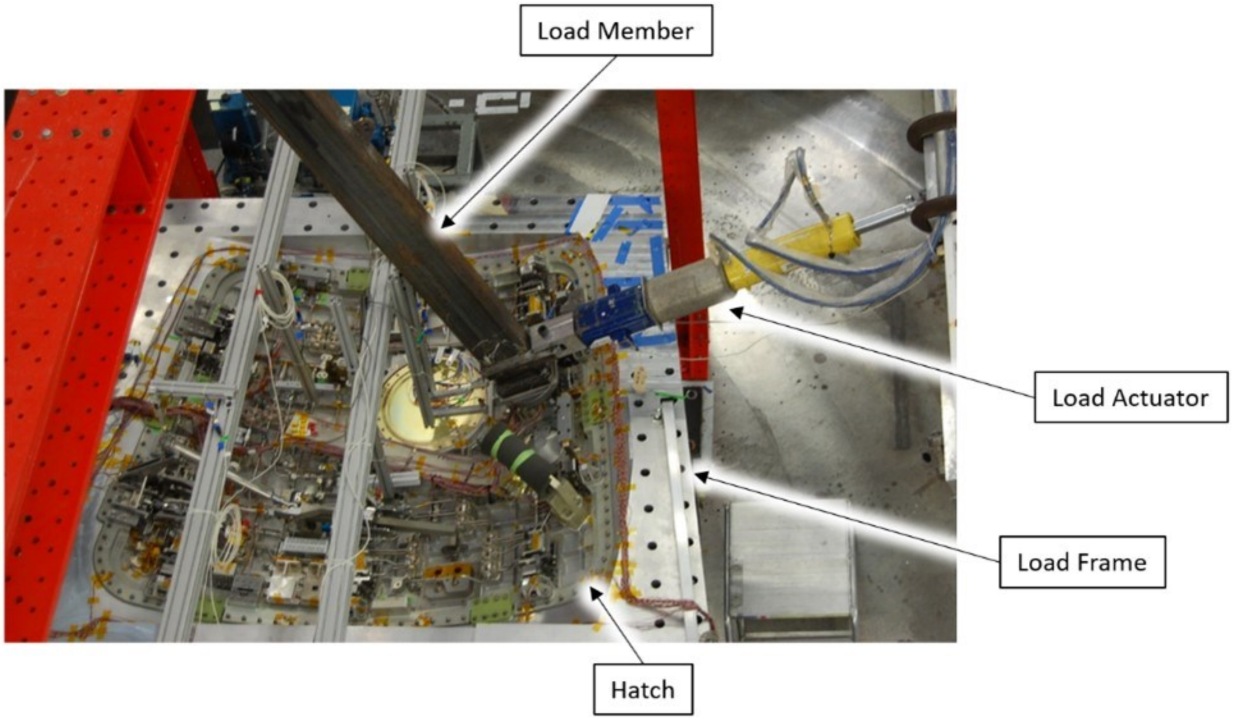

Figure 14: EDU LAS Hatch Static Load Test

FEM results represent an approximation of the predicted response and should be verified by test methods. Figure 14 shows the hatch static load test performed to verify FEM results.

In some cases, a course FEM is overly conservative and required higher fidelity FEMs to meet mass critical design requirements while demonstrating positive margins of safety (MS).

During analysis it was found that the extreme abort environment caused high deflections on the hatch structure inducing large loads. To counter these deflections, normal and tangential hard stops were added to the parameter of the hatch. It was found however that due to the environment these hard stops did not reduce the loads to the extent expected. Rather they created additional load paths that do not necessarily share the load. The normal and tangential hard stops were kept in the design since they did aid in reducing hatch structural load, even though the reduction was not as high as anticipated.

Thru multiple iterations of structural analysis of the hatch and components installed onto the hatch it was found that due to the high vibe environment, the addition of mass to overcome of the induced loads would sometimes create a negative reinforcement loop where more mass created higher loads, which in turn required more mass and so forth. Therefore, alternative design approaches were sought to mitigate this loop such as hard stops to limit deflections and alternate materials to allow higher deflections.

Hinge Testing

The hinge design is a 4-bar linkage mechanism. When the hatch is in a closed position, the hinge hard stops engage and allow load to transfer between the hatch and frame.

Real time monitoring of test data with strain gages, digital imagery correlations and actuator feedback data was required to protect the test article and correlate the analysis models. Great communication, trust and patience between the analyst and test team is required to maintain control of a 6 degrees of freedom system.

Statically testing this mechanism required weeks of trial and error, influence coefficient load cases and many adjustments to load/control systems to collect enough data to correlated FEM prediction models. Test campaigns of this duration and complexity require test discipline from the entire team. Despite the team's best efforts and good test discipline, repetitive activities can lead to human error. Approaching the end of the test campaign, a simple hydraulic value for the load jacks was configured incorrectly and resulted in an unexpected test failure of the article. The test campaign was considered successful because of the data collected; however, the failure was an important lesson related to test discipline. Figure 15 is the hinge in a closed position, ready to statically test.

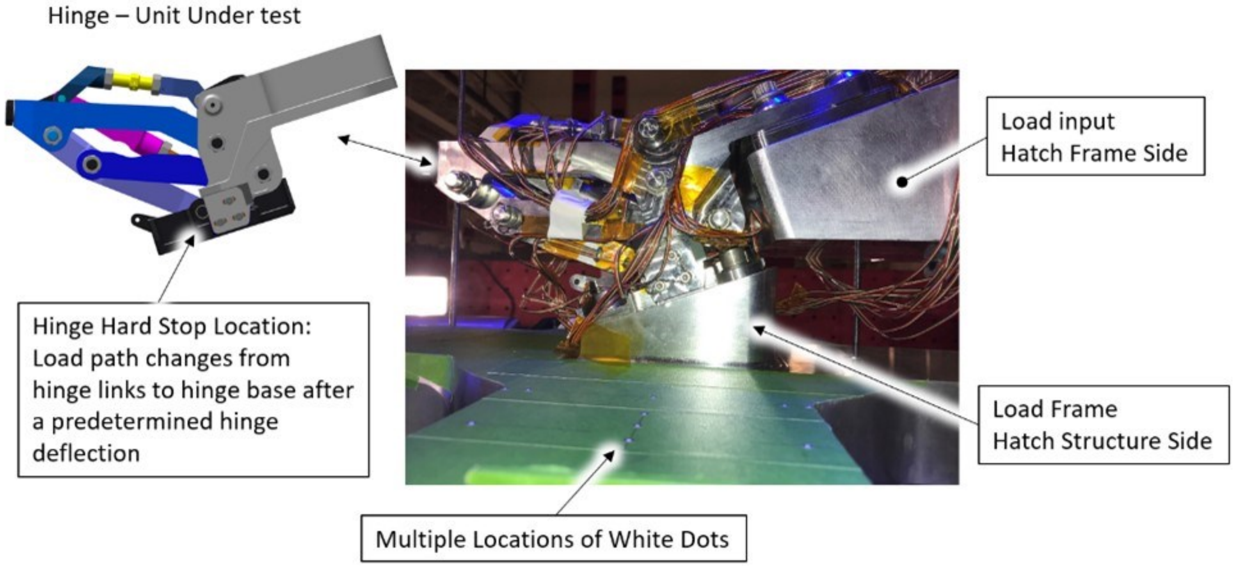

Figure 15: Hinge Static Load Test

Lessons Learned

- Test as early as you can: many issues found during testing were harder to overcome due to flight hardware already built to maintain schedule.
- The normal and tangential hard stops were added to the perimeter of the hatch to reduce hatch deflections, however due to such an extreme abort environment the overall reduction in structural load was not as initially expected.
- The pneumatic latches provided a system that was less sensitive to hatch structure deflections than the original mechanical latch design.
- Testing found that if external spiral lock rings are not installed correctly, they can back out of the groove during a vibe environment. After external spiral lock rings were found to be backing out of the groove during a high vibe environment, an installation step was added for installing these rings

where the outer diameter of the installed ring was measured and verified to be within tolerances. If they were out of tolerance, it could indicate one of the spirals may be seated improperly within the groove or other tolerances may not be met for proper installation.

- The use of COTS or vendor supplied items may look like the best option on paper but weighed against packaging, performance and reliability of a customized part, the COTS item may not be the best suited for the application. The LAS Hatch used COTS items such as solenoid valves and gas struts but designed the latch linear actuators in house.
- Adding mass to take the high loads created a negative reinforcement loop where more mass created higher loads which required more mass and so forth…

Conclusion

The design and development of the LAS Hatch proved challenging due to the abort environment provided by the LAS rockets as well as providing a safe and reliable crew egress during on pad emergencies. The pneumatic latches proved to be a lighter and reliable system to the mechanical alternative. They also proved successful for timing requirements during Side Hatch/LAS Hatch emergency egress tandem testing. The LAS Hatch extreme environmental levels provided by vehicle on pad, launch, in flight and possible abort activities provided challenging opportunities to develop test campaign approaches. The qual testing including Hinge Static load test and Tandem testing as well as AA-2 abort and Artemis I flight tests provided evidence of a safe and reliable LAS Hatch for future Artemis missions.

Figure 16: *Artemis 1 uncrewed test flight, November 16th, 2022, at Cape Canaveral launch site*
Photo Credit: NASA/Keegan Barber

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