Design of a Deployable Vacuum Seal Cover for the Europa Clipper's MASPEX Instrument

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Abstract

The Mass Spectrometer for Planetary Exploration (MASPEX) instrument on the Europa Clipper Spacecraft required a deployable mechanism to hold vacuum and maintain a leak rate less than 1E-8 Pa*l/sec (1E-10 mbar*l/sec) throughout ground operations, launch, and interplanetary travel until commanded to deploy. This custom-designed vacuum cover mechanism utilized a metallic H-seal to meet stringent leak and cleanliness requirements. The cover also relied on a significantly scaled-down version of heritage clamprings to provide retention of the high seal loads prior to deployment. Due to the fine measurement capability of the MASPEX instrument, a hermetic actuation device and minimal non-metallic components and finishes were used.

This paper addresses the driving requirements, design, integration, and lessons learned for use of a deployable knife-edge seal. Design challenges of developing a miniature clampring (approximately 12.7 cm (5.0 in) outer diameter), incorporating micro-switches, limiting weight, and designing a mechanism with minimal non-metallic components are included. Additionally, the mechanism design path, from trade studies through successful protoflight testing, including a late system requirement change leading to the need to add redundant non-evaporable getter (NEG) pumps to the critical sealing component, is explored.

Introduction

The Europa Clipper spacecraft is planned to launch in 2024 to determine if Jupiter's moon Europa harbors conditions suitable for life [1]. The spacecraft will orbit Jupiter and make 40 to 50 passes over the moon's surface [2]. One of the instruments on the Europa Clipper is the Mass Spectrometer for Planetary Exploration (MASPEX) instrument. This instrument will sample and analyze gases from the plumes venting to space from Europa's surface to study the moon's ocean surface and atmosphere [3]. As the MASPEX instrument has a mass resolution hundreds of times finer than any hardware previously sent to space, all surrounding components were selected to minimize the use of non-metallic materials to limit outgassing near the instrument aperture [3]. In order to protect the instrument before space flight use, a deployable cover is to be mounted onto the instrument's antechamber (at instrument aperture) that can hold the required hermetic seal. Design, manufacturing, and test of the vacuum cover mechanism was performed at Sierra Space (Sierra Nevada Corporation) for Southwest Research Institute (SwRI).

Design Requirements

The deployable vacuum seal cover for the MASPEX instrument was a custom design due to several unique and challenging requirements. The cover is required to complete a single deployment in flight following interplanetary travel upon command. It is rated for 12 years of spaceflight operation as well as 12 years of ground use. The design driver for this mechanism was the sealing requirement of < 1E-8 Pa*l/sec (1E-10 mbar*l/sec) helium leak for ground, launch, and flight environments before release. This leak requirement is equivalent or greater than the best commercially available static seals, and is at the noise floor of most helium leak detectors. The MASPEX cover is required to maintain a hermetic seal to ensure that the instrument remains free of contaminants to protect the sample for subsequent error-free analysis. For similar reasons, materials were selected for a metallic seal and related internal chamber surfaces to avoid contaminants like dissolved hydrogen, nitrogen and argon gases. Any internal surfaces containing

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dissolved gasses would outgas and negatively impact the instruments analytical results. All components of the cover mechanism were required to be retained below the instrument aperture following release, in order to not occlude the aperture, limiting the input into the instrument. Additional requirements include application of redundant heaters and springs (for cover open), as well as a mass limit less than .86 kg (1.90 lb).

Finally, due to the instrument and mechanism's position on the spacecraft (cantilevered away from the spacecraft) and functional requirement to maintain seal throughout environmental loading, the operational temperature and vibration requirements were key design drivers. Vibration, (X-Axis, perpendicular to aperture and sealing surface) was high at 26.1 gRMS. Cover operational (flight) temperatures ranged between -60°C to 80°C with a mechanism bakeout requirement of 220°C.

Flight Mechanism Design

The flight design evolved from a series of developmental design and test iterations as test results revealed new information and requirements evolved. Although the final flight design deviated from the prototype concept, the functionality of the cover as a whole remained consistent. The main structural components of the mechanism, including the rings, clampring, seal plate, and hinge structure were composed of Titanium 6AL-4V.

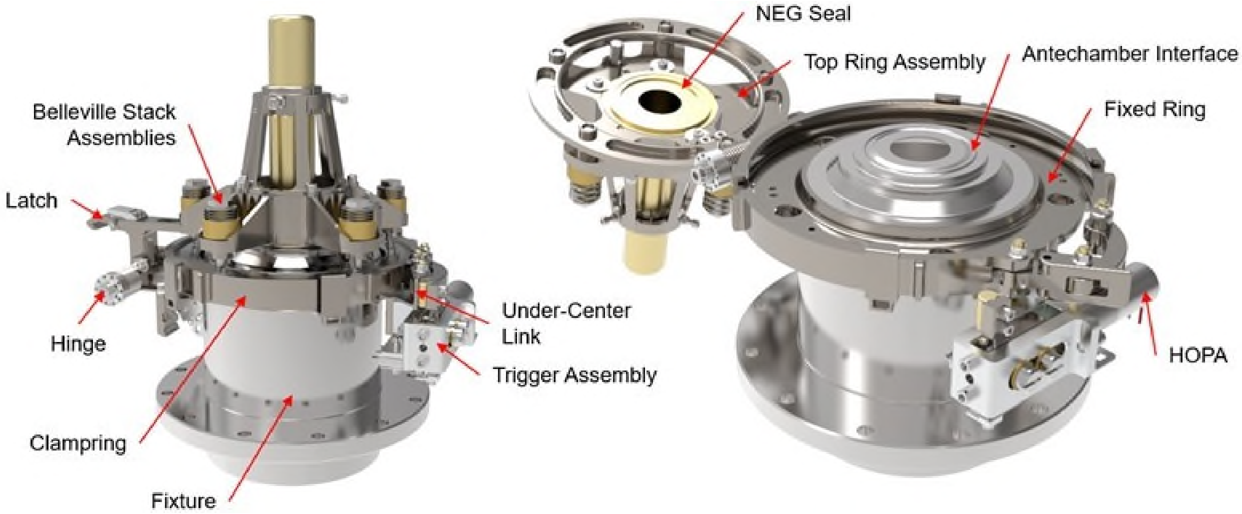

Figure 1: Component positions on cover mechanism (Left) Stowed rendering of flight mechanism mounted on antechamber, (Right) Deployed rendering. Credit: Sierra Space Corporation

The mechanism incorporates a modified Bostec capped H-seal to achieve the 1E-8 Pa*l/sec helium leak requirement. The seal is made from a C107200 copper alloy, with a gold-sputtered finish for corrosion resistance. C107200 copper was selected due to its CTE similarities to the instrument interface. Additionally the material, in conjunction with the H-seal design, had an acceptable force to load, and did not require any non-metallic components to retain the required leak rate. The seal was loaded perpendicularly to the surface with a GSE fixture. Hinge compliance (in-plane as well as axial rotation degrees of freedom) was incorporated to allow for proper loading and alignment of the seal. The design insured the seal remained parallel and did not arc down onto the knife-edge interface on the instrument prior to the engagement load event. For deployment, the cover rotates on a hinge line with 1.27 mm (0.050 in) of axial pin clearance to account for component tolerances and seal loading travel. The seal is designed with an extension to support redundant NEG pumps, which are required to mitigate outgassing during vacuum pump down of the instrument. This extension is supported by a structure that had three clamps surrounding the extension, preventing displacement of the seal during vibrational loading of the mechanism. These clamps are specifically designed with recessed features to ensure two lines of contact each onto the seal. This ensures the seal will not fail due to the attached support structure reaction loads during exposure to the vibration environment.

The top ring assembly is held in place using a miniaturized clampring with built-in shoes. The clampring, approximately 12.7 cm (5 in) diametrically, holds the top and fixed rings in place. Tension in the clampring, approximately 1780 N (400 lbf), is held with an under-center latch and trigger assembly. The clampring tension was derived to react the engagement loads required to set the cover seal. In accordance with heritage design, the clampring is machined in a free state larger than the radius of the band catchers, and its stowed state, such that upon deploy, the clampring is held under its own elastic forces. The catchers hold the clampring in place for the remainder of the spacecraft's operations, preventing microphonic excitation. The geometry of the linkage is designed to prevent the under-center link from reaching the over-center condition, thus ensuring the clampring always wants to open. The trigger assembly holds the latch in place until actuated using a Sierra Space High Output Paraffin Actuator (HOPA) mechanism. The trigger is held preloaded, before actuation, via compression springs housed in the trigger assembly. The trigger slides along a mounting bracket with redundant bushings. The HOPA used, an EH-3525 model, is hermetically sealed and provides 222 N (50 lbf) upon command using redundant heaters [5].

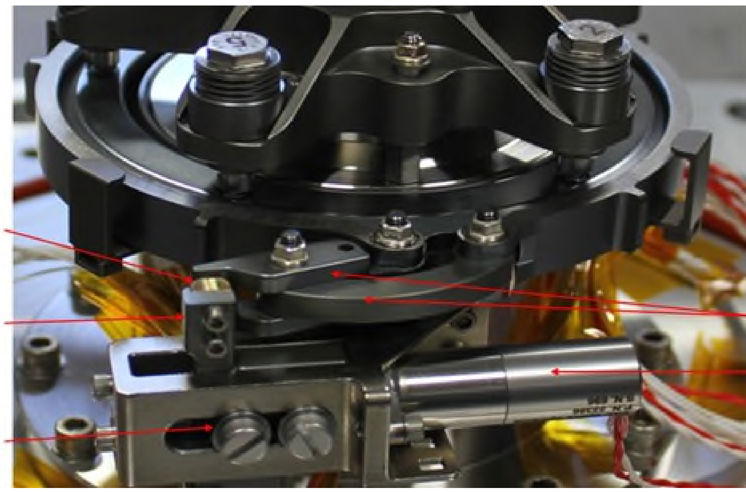

Figure 2: Stowed clampring and under-center latch on flight mechanism. The under-center latch assembly required use of components with different materials and the use of non-evaporable lubricants. Credit: Sierra Space Corporation

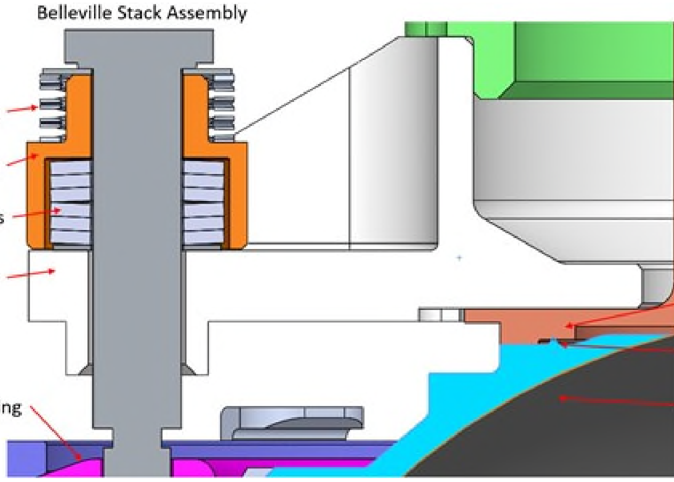

Figure 3: Belleville stack assembly isometric cut view. Also shown is the knife-edge cut into the H-seal from the antechamber sealing interface. The sealing interface is preloaded for flight by five Belleville washer stacks. Credit: Sierra Space Corporation

The seal is engaged onto the knife-edge antechamber via an external ground support equipment (GSE) fixture that loads the seal through the load plate. The seal protects an aperture slightly larger than 20.3 mm

(0.80 in). Following engagement of the seal, the seal is retained onto the antechamber with approximately 13.3 kN (3000 lbf) via five Belleville stacks. Each stack was characterized prior to integration and shimmed to ensure the desired preload when torqued to a hard stop. The Belleville stacks provide force through the load plate, and are retained by threading into the top ring, and constrained before deployment with a clampring. Each stack also has a wave spring, which upon clampring deployment, acts to pull the top ring away from the interface surface ensuring the top ring assembly clears the clampring (Ref Fig. 3).

Actuation of the HOPA is confirmed with a micro switch located on the trigger assembly. The switch is closed and snubbed into place during launch operations and rides along a cam during mechanism release.

Upon release of the clampring latch, the top ring assembly is released from the fixed ring and moves to the deployed state via two redundant torsion springs reacting at the hinge line. These springs are aided by a kickoff plunger, oriented 180 degrees from the hinge line, to mitigate any stiction of the seal onto the antechamber. Testing of the mechanism indicated that stiction and the force to release the seal was negligible. When fully deployed, the top ring assembly contacts a diving board hard stop. The diving board hard stop acts to react the deployment force from the torsion springs and kickoff plunger. Additionally, the top ring assembly is preloaded against the diving board and latched into place following seal deployment. A micro switch is located on the hinge line, to indicate when the cover is clear of the clampring towards the deployed condition. The switch is closed during stowed operations and rides along a cam as the top ring assembly deploys.

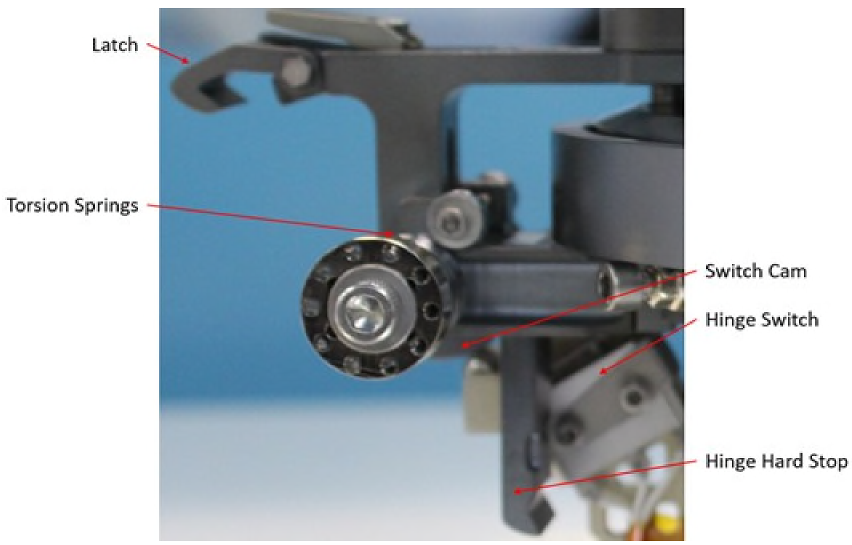

Figure 4: Hinge and latch assembly in stowed state. Latch assembly prevents rebound of cover and locks the upper ring assembly below the instruments aperture following mechanism deployment. Credit: Sierra Space Corporation

Due to the sensitive nature of the MASPEX instrument, careful consideration to all non-metallics and use of dissimilar metals was taken for the cover mechanism. No non-metallic materials were used in the sealing interface, which is exposed to the instrument aperture. For sliding surfaces of the mechanism, Dicronite solid-film lubricant was used. For the hinge line, the structural components of the mechanism, composed of titanium 6AL-4V, rotated on a 15-5 stainless steel hinge pin (undersized to provide compliance for seal loading), with the rotating surfaces separated by beryllium copper washers. The loading surfaces of the clampring and rings were also lubricated with the Dicronite solid-film material. Care was taken to properly burnish the rings and clampring before integration, and visual inspections were conducted after all functional testing to ensure that the surfaces were not degrading under the clamping loads. The solid-film coating was used on the prototype, EDU, and flight builds, and did not show degradation during functional and environmental testing. Additionally the under-center latch (Dicronite coated titanium 6Al-4V) component is loaded on the trigger assembly, and slides along a C65500 bronze shuttle when deployed.

The trigger shuttle rides on beryllium copper bushings along structural surfaces coated by Dicronite solid-film lubricant (Ref Fig. 2). More on this topic is discussed in the Trade Study section.

Although the cover mechanism was a unique custom design, several heritage components and concepts were incorporated. The cover design is based on an optical cover for NASA's Thermos-Spheric Temperature Imager. This design was updated to integrate the H-seal and to mount on the MASPEX instrument antechamber. The retention method is a modified clampring, based on a heritage clampring and HOPA mechanism for Cassini's Plasma Spectrometer, flown on the Cassini orbiter. The EH-3525 HOPA has significant flight heritage as a part of Sierra Space's paraffin actuator product line with over 20 years of spaceflight heritage. Bostec H-seals also have NASA flight heritage.

Mechanism Developmental History

A number of trade studies and engineering development units proceeded the final flight design. The following describes the history behind this cover mechanism's development. The initial concept for the cover mechanism incorporated a yet to be determined vacuum seal retained by a clamped interface to the MASPEX instrument's aperture. Design started around retaining the seal with a marman type clampring, however a pyro release of the clampring (commonly used) would have to be replaced with a lower shock release mechanism. This door cover was to be driven by torsion springs to move the door from the stowed to deployed state.

Trade Studies

The cover system design evolved from a series of trade studies to investigate potential seals capable of meeting the system leak requirement. This seal was originally required to meet a <5.0 E-10 Pa*l/sec helium leak requirement, without the use of non-metallic components with all surfaces free of dissolved hydrogen, nitrogen, and argon. The leak requirement was later relaxed to "just" 1E-8 Pa*l/sec helium leak. Further limiting design options was the deployable aspect of the seal cover. Design considerations were evaluated against required seal load (engagement and retention) as well as seal separation dynamics. Low engagement sealing force was critical to ensure the cover's mount (antechamber/ thermalizing chamber) would not be overloaded during mechanism integration. Additionally, potential seals were assessed for reusability, flight heritage, and cost/lead-time.

The seals investigated during this phase of the trade study were Bostec H-seals (cap, engaged exclusively on one side, and standard, engaged on two sides), conflat seals, delta seals, and metallic O-/C- rings. The H-seals, and the conflat seals were the highest scoring seals following the initial trade study. These seals scored the best because of effective performance in two key areas: leak rate and material composition (i.e., minimal leak rate and nonmetallic material composition). The H-seals also exhibited lower sealing force characteristics compared to other seals investigated. They function by engaging a knife-edge into a recessed flat surface on the seal. Load is taken through a positive stop on the seal to prevent overload of the seal once the knife-edge is fully engaged into the sealing surface [4] (Ref Fig. 3). The geometry of the knife-edge cut into the sealing surface is different than that of a conflat seal, and results in a lower necessary seal engagement load as compared to conflats.

Following initial trade studies, the capped H-seal was selected for additional helium leak checks. Note that these seals are typically used statically for vacuum tubing. The seal was tested under multiple configurations to determine the optimal seal material and interface engagement for the cover mechanism. Seal materials tested including 1100 aluminum, 200 nickel, and C107200 copper. Engagement depth of the knife-edge was characterized (.127 to .203 mm (.005 to .008 in)). This engagement depth study was critical and helped establish materials that required low engagement force while minimizing leak rate.

The seal configurations were subjected to thermal environments (25°C to 180°C) to ensure that the leak rate of the seal did not violate the leak requirement during thermal extremes or transitions between hot and cold. The seal configuration was set up in an enclosed chamber following seal loading, subjected to vacuum on one side of the seal, and helium pressure (up to 689 kPa (100 psi)) on the other (Ref Fig. 11). Helium background checks and internal calibration of the leak detector were conducted before and after helium pressurization of the enclosure.

Trades and testing determined that nickel and copper H-seals exhibited the best sealing characteristics. CTE differences between the aluminum seal and the antechamber resulted in unacceptable leaks. Nickel and copper seals showed minimum leak rates when the knife-edge engagement of the seal was .178 to .203 mm (.007 to .008 in). Seals predominantly met the sealing requirements with knife-edge engagement of .127 mm (.005 in). There was a singular test event with the nickel seal at the maximum temperature that violated the leak requirement for the nickel seal. Further investigation into the leak suggested that this was due to a GSE error. It is critical to ensure all joints, valves, and interfaces in the test setup were correctly sealed to ensure that any leak detected could be accurately attributed to the seal being tested.

Following trades and testing, the copper seal proved to provide the best overall characteristics and was chosen for the mechanism for several reasons. First, it offered lower initial engaging loads. Second, copper is a better CTE match with the A286 antechamber interface. Additionally, it was determined that the copper seal would be sputtered with a gold plating to mitigate concerns about copper corrosion during spaceflight.

During testing, sealing performance of the seal flat and knife-edge interfaces were highly dependent on surface condition and proper loading. Components needed to be highly controlled to eliminate burrs, cuts, scratches and other surface defects. Any damage to the sealing surface resulted in reduced capabilities to hold leak at the required level. Load being applied perpendicular to the sealing interface proved critical. This load needed to be applied evenly around the knife-edge interface. The knife-edge cut into the H-seals needs to be crisp (Ref Fig. 5); rounded cuts due to uneven loading of the seal did not result in acceptable sealing interfaces. Following the conclusion of leak testing it was noted that negligible force was required to release the seal from the antechamber interface.

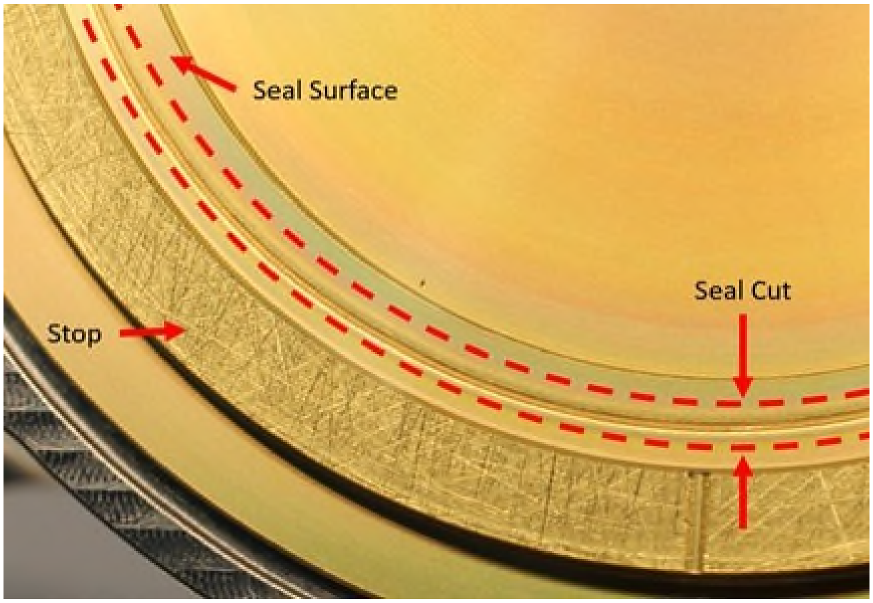

Figure 5: Desired cut from knife-edge onto capped H-seal. Cut is concentric relative to stop and sealing surfaces. The resulting cut is clean with not nicks or blemishes. Credit: Sierra Space Corporation

In addition to evaluating seal design, a trade study was conducted into potential actuation devices for the cover mechanism. Different models of heritage Sierra Space's HOPAs were compared for cleanliness (hermetically sealed), stroke and power output, mass, input power required, and redundancy for internal heater circuits. Trade study results indicated that the EH-3525 HOPA would best meet the mass and linear force actuation requirements for the cover release mechanism. The EH-3525 HOPA is hermetically sealed via welded bellows with sufficient stroke and output force for use on the cover. The EH-3525 HOPAs operational power required (5 W @ 28VDC) and mass (<35 g) were minimal, and met system requirements.

Lubrication choice for the sliding surfaces of the mechanism also posed a unique problem. Given the mechanism's location very near to and around the instrument aperture, a low outgassing lubricant was needed. As this requirement eliminated all wet and binder based lubricants, it pointed toward a sputtered lubricant such as MoS_2 or WS_2. Because key requirements for this mechanism included very low outgassing, sliding contact, very low cycle life, and the need for a very thin coating, Dicronite (sputtered WS_2) was selected over MoS_2 [6]. Previous space industry experience also indicated that rigorous application and handling practices were required to successfully use Dicronite in a spacecraft mechanism. All lubricated components were coated exclusively at approved vendors, with 100% visual inspection upon receipt. During assembly, contacting interface surfaces were appropriately burnished, and these surfaces were inspected and monitored during subsequent assembly and test to ensure that degradation or exessive wear did not occur.

Prototype and EDU Development/Testing

The initial cover mechanism for the prototype and engineering development units was designed following the trade studies. This cover incorporated a copper capped H-seal and the EH-3525 HOPA. These non-flight builds were intended to prove out the cover concept to the TRL6 level to show that the cover met the sealing requirements through preliminary vibration levels and thermal cycling, and that it could functionally deploy following environmental testing. The cover was designed around the capped H-seal, which was clamped into place on top of the surrogate antechamber using a load plate. This load plate was fixed in place by two rings (one fixed onto the antechamber, one free to release) which were secured by a clampring. The clampring was held in position using an under-center latch, released by a trigger assembly actuated by the EH-3525 HOPA. Following the paraffin actuated unlatching event, the cover opens along a hinge line powered by redundant springs, and preloads it against a set of leaf spring to dampen the impact loads.

Given the material requirements for the mechanism, wet lubricants and the binder-based MoS_2 dry-film lubricants were not acceptable for use on the cover due to outgassing concerns and their propensity to produce particulates. A solid-film lubricant, Dicronite, was selected for use on the cover.

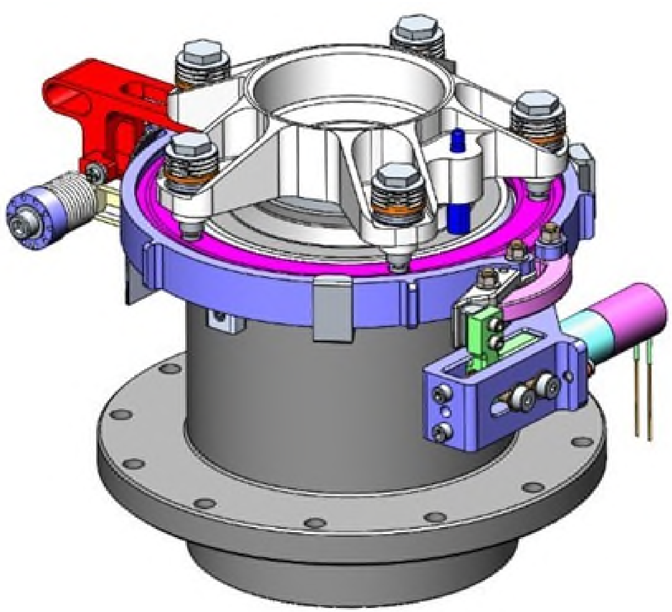

Figure 6: Prototype vacuum cover mechanism concept. Credit: Sierra Space Corporation

Clampring tension adjustability was designed into the mechanism trigger at the end of travel for the under-center latch (a new method of retaining a clampring). Initial loadings of the clampring (with or without the rings) showed that these shims provided negligible adjustability for the tension in the clampring. Further testing showed that by the time the under-center link reached the end of travel, as designed for the mechanism, adjustments in angle correlated to limited changes to the clampring tension; the greatest change in tension to link angle occurred significantly before the transition point between over and under-center. This resulted in a design modification to the under-center linkage for the prototype being slotted at assembly to achieve the desired tension in the clampring. Clampring tension was confirmed with force testing at the linkage and gap testing of the rings.

Retention load on the seal, before release, was set with five pre-configured sets of Belleville washers. These Belleville stacks were combined with wave springs to pull the top ring away from the clampring when the mechanism was deployed (Ref Fig. 3). Additionally the load plate featured a kick-off plunger to release the cover under any stiction events. The plan for this cover was to load the seal using the five Belleville stacks. The stacks threaded thru the top load plate into the free ring. These stacks were to be loaded incrementally in a star pattern in order to ensure the seal came down evenly. The required seal impregnation load was designed to be 17.8 – 22.2 kN (4500 – 5000 lbf). This load value accounted for the minimum engagement load measured during trade studies, with margin added to ensure complete engagement of the seal. Following initial impregnation of the capped H-seal, the retention load for the seal was only required to be approximately 13.3 kN (3000 lbf) (value also heavily margined to ensure proper preload during environmental exposure).

The design of this mechanism was a delicate balance between creating a cover that could keep a hermetic seal and then fully release upon command. Testing during the initial build of the first unit (TRL6 testing) revealed several functional issues that required design updates. The first issue involved the capped H-seal seal. Although the H-seals are capable of handling minor positional misalignments, it is critical that the seal is guided onto the knife-edge interface [4] (Ref Fig. 5). It is also critical to ensure that nothing interferes with the positive stop of the seal. The initial design had the capped H-seal secured in place using a clamp around the OD of the seal. Unfortunately, compliance built into the hinge that allowed the seal to engage properly was not enough to allow the top ring assembly to seat correctly on the antechamber. This drove a design change to replace the original seal securing ring with less obtrusive retention features.

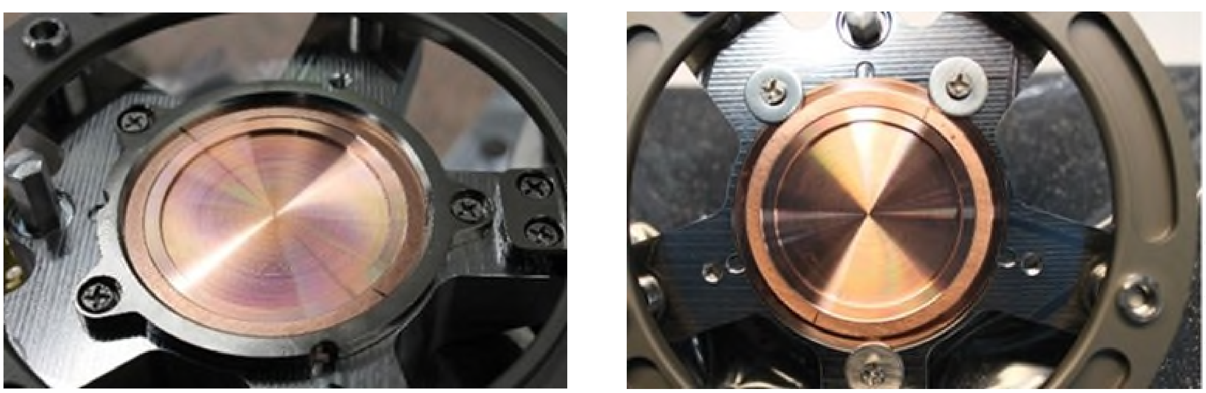

Figure 7: (Left) Original seal retention method (Right) Updated seal retention method. The original seal retention method did not give proper clearance to the antechamber to allow for the seal to be loaded correctly, and prevented proper deployment of the cover. Credit: Sierra Space Corporation

Following the change to the seal retention, the cover mechanism was loaded. Care was taken to ensure that the seal flat was properly oriented onto the knife-edge surface after the first operational loading resulted in a seal that was only 75% engaged on the sealing surface due to a concentric misalignment. The seal was biased in the load plate to counter the load plate being biased by the torsion springs. Once that was corrected, integration and test resulted in proper concentricity of the knife-edge cut onto the seal. Following several stow and load cycles of the prototype cover, it was noted that the cut into the seal was rounded at the top, which resulted in undesirable sealing conditions. Further investigation into the loading procedure found that incrementally loading Belleville stacks was insufficient to ensure proper penetration of the knife-edge into the seal. To remedy this, the mechanism was loaded using an arbor press to depress the load plate, ensuring that the knife-edge seal engaged the mating interface of the surrogate antechambers knife-edge perfectly perpendicular to the seal. A GSE fixture was developed to ensure proper load application of the seal. This fixture mimics the functionality of the arbor press through two power screws, torqued simultaneously to load the cover. The GSE loading fixture mounts on the fixed ring and loads the seal through the load plate.

Following several confidence test deployments of the prototype unit, the front band catcher for the clampring showed significant yielding, to the point where it was no longer functional. Analysis of the high-speed video showed the under-center latch and clampring system resulted in more energy input into the catcher than anticipated. This resulted in a catcher material (Aluminum 6061 to Titanium 6Al-4V) and thickness change. Subsequent deployments confirmed that the new catchers functioned as-designed without deformation.

Characterization of the Belleville stacks for the prototype build also resulted in a desired change to the mechanism. The prototype mechanism relied on previously characterized spring stacks to be torqued to a certain height with gauge blocks indicating deflection located on either side of the stack. This was a needlessly tedious process with potential to not be as reliable as desired; every .025 mm (.001 in) deflection of the stack resulted in significant load changes for the stack. It was determined that all future designs should have a hard stop feature around the stacks to ensure consistent retention loading of the seal. To make the stacks adjustable, shims were placed inside the sleeve to allow for the desired load to be dialed in during Belleville characterization.

Loading of the EDU clampring showed that the under-center linkage needed to be slotted differently than the prototype build, in that additional slotting was needed. Further inspection of the rings being clamped by the clampring showed the rings were minimally greater in their outer diameters as compared to the prototype unit. Further testing with varying sizes of rings, showed that the final tension of the clampring was highly dependent on the size of the outer diameter of the rings. This resulted in the tolerance of the outer diameter feature for the rings being tightened for all subsequent builds.

Updates to the mechanism design and loading procedure resulted in a prototype cover that was sealing properly during functional/confidence testing. The prototype build was then exposed to vibration in all axis and subjected to thermal cycling (-45°C to 175°C). The cover mechanism was helium leak checked continuously during each environmental test. The prototype cover successfully passed all environmental testing while maintaining the required sealing interface throughout. Following environmental testing, the cover was successfully deployed. The cover design was updated with the lessons learned from the prototype build and released at the non-flight level. Environmental testing was repeated on the EDU cover proving the concept and giving high levels of confidence in the design.

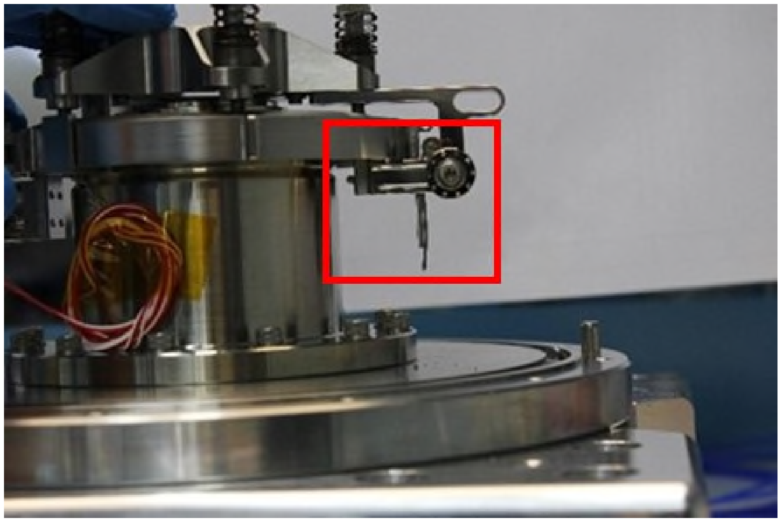

Figure 8: Yielding of leaf springs following deployment of the cover. The leaf springs on the prototype cover yielded following multiple test deployments. Credit: Sierra Space Corporation

Following the EDU test campaign, two updates were needed for the flight mechanism. The first was to update the stop for the top ring assembly following release. Multiple undesirable features were noted with the leaf spring stop. Following multiple deployments, the leaf springs began to yield. Further testing of the mechanism (including over 50 releases into the leaf springs) showed that the yielding stabilized after the first 5-10 deployments, however, a more robust stop and capture system was determined to be necessary for the flight built. Additionally, the leaf spring stop did not absorb enough energy of the cover after contact, causing the cover to bounce back over the instruments aperture. The cover would eventually rest on the leaf springs as designed. Although the door bouncing did not violate any requirements, it was determined that the flight build must retain the cover in place following deployment without the cover re-entering the aperture of the instrument to prevent any damage to the antechamber (surrogate or flight) for future units.

Additional lessons were learned during the development of the test fixture. Initial base readings showed that background helium could be sensed by the LACO Titan Test Machine (LACO) if not properly vented. This was isolated following gradual increases in helium being detected by the machine throughout prototype vibration testing. The LACO was blanked off; following reset and pump down of the system, the helium leak detected had climbed significantly above what had been detected during previous background calibrations. It was determined that the helium from previous pressurizations had built up in the smaller (than the manufacturing floor) test room. This was mitigated by opening the test room during helium purge events, and piping the LACO exhaust outside the testing area. Additionally, it should be noted that each interface in the test set up presented a potential leak point. Each of the interfaces had to be meticulously secured and checked (using a Helium sniffer bottle) to ensure that the cover mechanism would be isolated as intended.

EDU to Flight Design Build and Test

Before updating the development design of the vacuum cover mechanism to flight, a system-level requirements change was levied against the mechanism. It was determined that redundant NEG pumps were necessary to counter outgassing inside the instrument. The NEG pumps, and subsequent housing, could not be attached directly to the antechamber due to the antechamber's function as the MASPEX instrument input component. The cover's H-seal was determined to be the only location to attach the NEG pumps. This added a new wrinkle in the challenge of designing a deployable interface that could maintain a hermetically sealed chamber. Additional design iterations were required to accommodate the seal growth into the cover, hopefully without a complete re-design of the cover mechanism.

Even though the NEG pumps represented a relatively minor mass increase, the offset cantilevered nature of the housing components, and related heating requirements drove a design change to the seal and surrounding structure. For the NEGs to function, they need to be heated to over 500°C for 10 minutes. Because antechamber vacuum must be pulled prior to NEG activation, NEG heating was required after the cover system was sealed onto the instrument's antechamber. Due to the risk of the seal failing from rapid CTE changes, NEG activation was required to occur away from the critical seal interface with enough distance to create an effective heat sink. This drove a design change to attach a structural extension to the H-seal that offset the NEG pump approximately 9.5 cm (3.75 in) away from the seal interface, deviating significantly away from the original flat seal design.

Several design updates accommodated the extension change to the critical sealing component. A bore was added to the load plate for the NEG seal to pass through. Additionally, the extension in the H-seal had a marginal fillet at the extension point (1.9 mm (0.075 in) radius), which resulted in a high-stress point. It was analytically determined that launch loads would break the NEG extension off of the H-seal if not properly supported. A "tree" support assembly was integrated into the cover to properly support the seal. This support structure is attached to the load plate to offload the mass of the NEG extension under launch loads and to prevent related deflection from compromising the seal. This assembly features three radially adjustable clamps. Each clamp has a recessed feature to ensure two lines of contact per clamp on the extension in order to reduce associated Hertzian contact stress (Ref Fig. 9). These clamps were lightly snugged against the seal extension, and then locked into place. The support structure is designed to be installed on ground prior to launch following activation of the NEGs.

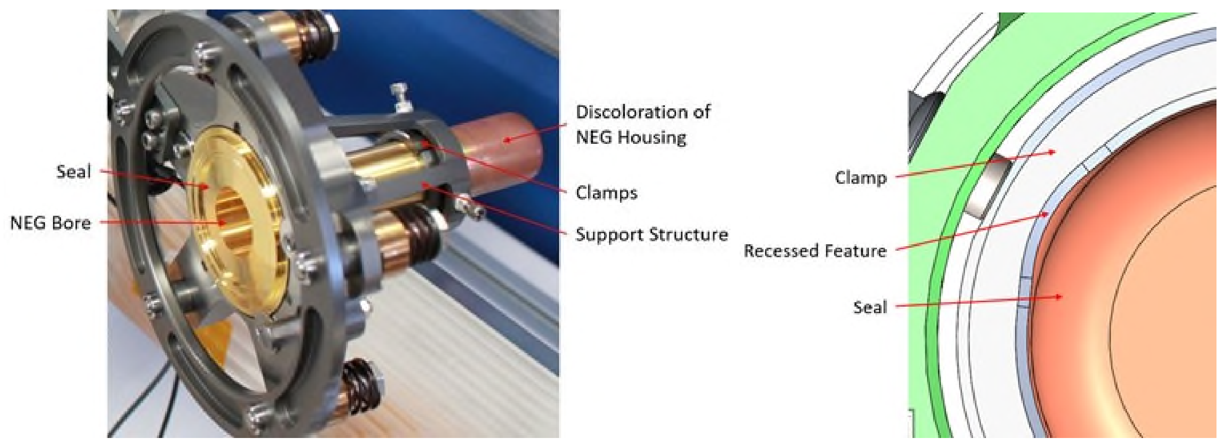

Figure 9: (Left) NEG Seal following activation with support fixture installed. The support fixture was required to prevent deflection of the NEG pump seal housing. The NEG seal was discolored following activation where it was heated to 500°C for over 10 minutes. (Right) Clamp interface onto seal. Cut in clamp ensures two lines of contact on seal to limit Hertzian stresses. Credit: Sierra Space Corporation

In addition to the NEG support flight design update, the stop design for the cover was improved and a latch was added. As the original stop design on the prototype and the engineering development units exhibited significant bounce back of the cover into the instruments aperture, the leaf spring stack up was replaced with a single flexure (diving board). The new design was analyzed to optimize thickness, avoiding over stress (yield), while maintaining adequate force and deflection parameters for force attenuation following deployment. A latch was incorporated to prevent the deployed cover interfering or damaging the instrument aperture; it was designed to activate with the inherent hinge compliance and catch underneath the diving board to secure the cover following deployment (Ref Fig. 4).

It was also determined that two telemetry switches were necessary. The first switch was required to indicate actuation of the HOPA. The switch was added underneath the trigger holding the under-center link and guided along a cam which activated the switch once the link was released. The second switch was required to indicate the cover opened clear of the clampring and was integrated into the hinge components of the cover. This switch was placed alongside the diving board and was depressed with a cam attached to the hinge line, toggling when the cover was released and significantly routed towards its stowed condition.

Finally, minor improvements were also made to the kickoff plunger to replace a retention ring with a nut and washer hard stop. Additional band catchers were also placed around the mechanism to ensure the clampring was fully retained following deployment, and would not rattle during interplanetary travel to meet a new microphonics requirement.

Flight Cover Testing

Following implementation of design changes to the EDU unit, development testing was conducted to validate design changes. Before environmental testing, to validate the NEG seal activation process, the NEG seal was sealed and activated. An induction heater was positioned around the NEG and a heat sink was connected to the seal. Thermocouples were placed at the base of the seal to monitor temperature changes ensuring that the knife-edge interface would not be damaged during the activation process. The thermocouples showed that the base temperature did not notably increase. This result greatly alleviated concerns that NEG pump operations would compromise the seal and fail the helium leak requirement.

Helium leak checks were conducted with a LACO TitanTest machine. This machine was calibrated such that the minimum detectable helium leak rate in the ultra-fine vacuum mode was at the leak requirement (at the time) for mechanism (<5.0 E-10 Pa l/sec). Leak tests were conducted by placing the mechanism, stowed and sealed on a surrogate antechamber, underneath an enclosed top hat (Ref Fig. 11). The surrogate antechamber was connected to the LACO machine and pumped down to vacuum. The top hat was then pressurized with helium. This enclosure was mounted on a vibration table or in a thermal chamber with helium leaks being monitored by the LACO during all tests. Standard calibration and background levels were conducted/recorded before and after each test to ensure accurate leak measurements.

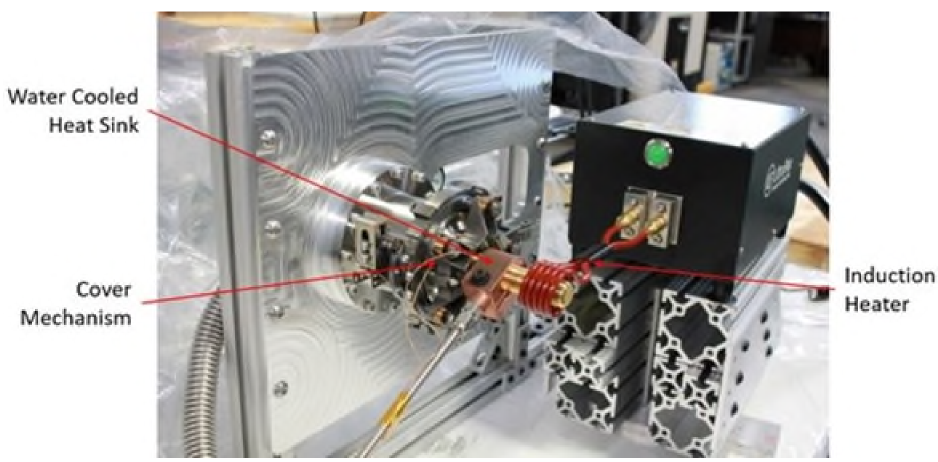

Figure 10: NEG activation and heat sink. NEG activation involved an induction heater heating the NEG pumps to 500°C. A water cooled heat sink was mounted to the NEG seal to prevent damage to the critical sealing interface. Credit: Sierra Space Corporation

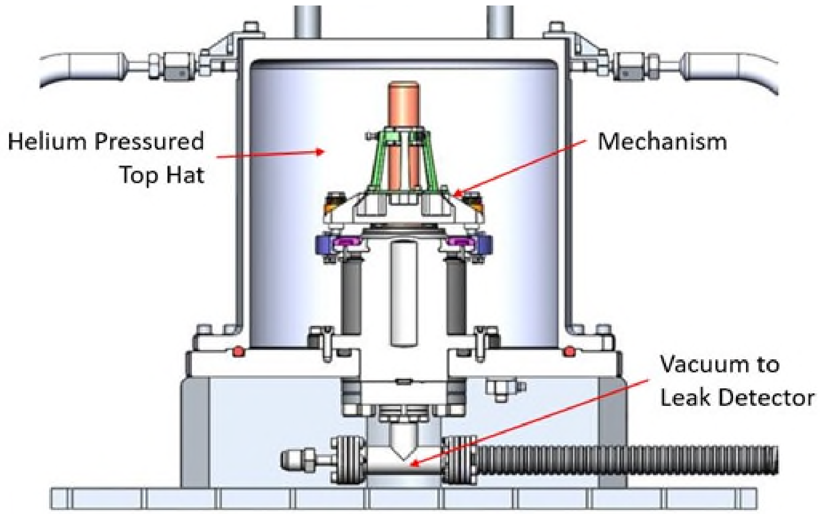

Figure 11: Leak chamber for cover mechanism. Helium was backfilled into a top hat, with a leak detector pulling vacuum on the other side of the seal, monitoring for He leak. Credit: Sierra Space Corporation

The leak requirement levied on the mechanism was at the noise floor of what could be detected using commercial vacuum/leak detector machines. It was noted during initial trade study testing that when the LACO was measuring at the noise floor, background (artificial) spikes were being detected. This posed problems for validating the sealing interface of the mechanism as these background spikes (although consistent both in size and frequency) occasionally violated the system level leak requirement. Additional data refinement was required to ensure that these background spikes were not artificially “failing” the mechanism interface.

Measurements were taken before all vibration and temperature cycling to develop background values to determine if any potential delta in leak rate was recorded during environmental testing. This method was developed during the trade study phase, and used throughout the remainder of the program.

Following NEG activation, the updated engineering development unit was environmentally tested to the updated flight vibration and thermal levels to ensure functional compliance. Fortunately, with the design changes implemented, the updated EDU mechanism was able to pass all environmental test (vibration and thermal cycling) and functionally deploy, clearing the way to move to the final flight build. The flight design was then built and tested to the updated environmental conditions. A full visual inspection was conducted on the seal following release to confirm that no yielding occurred and that no particles (from the NEG assembly) were generated during testing. The successful completion of these tests moved the mechanism to the TRL-8 level, and the flight configuration was shipped to Southwest Research Institute (SwRI) for final integration onto their instrument.

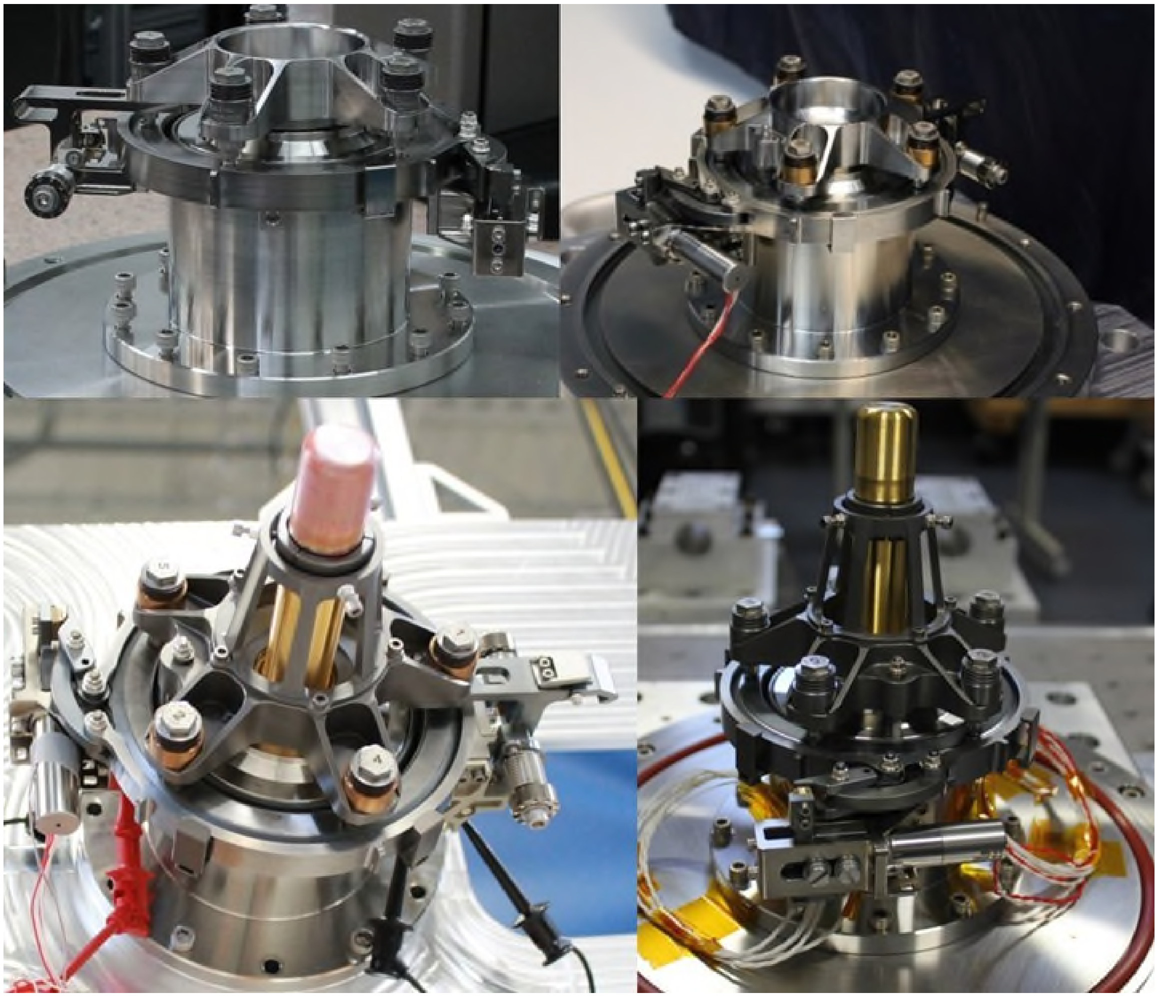

Figure 12: Cover mechanisms developed for MASPEX Instrument: (Top Left) Prototype Stowed, (Top Right) EDU Stowed, (Bottom Left) EDU (NEG) Stowed, (Bottom Right) Flight Delivery Unit. The cover design changed dramatically away from the previously tested prototype and engineering development units following the addition of NEG pumps attached to the critical sealing component. Credit: Sierra Space Corporation

Lessons Learned

Several lessons were learned during the development of a deployable cover capable of holding a hermetic seal from prototype to flight.

Hermetic Sealing

- H-seals and conflat seals are ideal for hermetically sealing interfaces, especially when metal on metal interfaces are required.
- It is critical that the sealing surface of H-seal and knife-edge interface are pristine surfaces free of burrs, nicks, and markings.
- Knife-edge interfaces need to be able to fully engage with the sealing surface.
- When loading H-seals onto a knife-edge, the seal needs to come down consistently perpendicular to the surface plane. The seal cannot be rocked or unevenly engaged onto knife-edge during loading.
    - For deployable mechanisms, this means compliance for the seal to come down perpendicular, and not on an extended radius from a hinge line (if applicable).

Clampring

- When tensioning a clampring with an under-center link, the majority of loading occurs during the initial movement of the linkage. There is limited load adjustability once the under-center linkage is near its end of travel towards the over-center condition.
- Variability in ring ODs, even by .025 mm (.001 in), greatly affects the final tension in the clampring. Those features need to be very tightly controlled to get repeatable results between mechanisms.

Helium Leak Testing

- It is critical to minimize all potential interfaces when testing minimal levels of Helium in the system.
- Excess background helium needs to be cleared from the immediate area of a leak detector
- The leak detector needs to be in pristine condition to measure at noise floor. Any undesirable particulates in the machine will prevent the system from pumping down and reading at the absolute floor.

Conclusion

A unique cover mechanism was required for the MASPEX instrument on the Europa Clipper Spacecraft that was capable of deploying a hermetically sealed contamination cover. Following trade studies and a non-flight build, a flight cover concept was built, functionally tested, and validated for all environmental loads and effects. System-level requirement updates necessitated design changes to the primary sealing interface late in the program. The updated design passed all helium leak checks, sealing to levels <1*10^-8 Pa*l /sec helium leak throughout all environmental tests. Several challenges were overcome throughout the development of this hermetically sealed cover system including management of deployable sealed interfaces, integrating miniaturized clamprings, minimal use of non-metallics, and application of under-center linkages. All these challenges resulted in invaluable technology advancement that can be applied to future flight designs and related space missions.

Acknowledgements

The authors wish to express appreciation to the MASPEX team at SwRI for their collaboration in the mechanism development and test. Specifically, Chip Beebe and Tim Brockwell's (SwRI) contributions and collaborations with the team at Sierra Space allowed this mechanism to make it through flight design and test. Development of the mechanism was made possible with the team's collaboration, frank discussions, and dedication to supporting development of a suitable cover for their MASPEX instrument.

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