Design and Test of a Deployable Radiation Cover for the REgolith X-ray Imaging Spectrometer

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Abstract

The REgolith X-ray Imaging Spectrometer (REXIS) instrument contains a one-time deployable radiation cover that is opened using a shape memory alloy actuator (a “Frangibolt”) from TiNi Aerospace and two torsion springs. The door will be held closed by the bolt for several years in cold storage during travel to the target asteroid, Bennu, and it is imperative to gain confidence that the door will open at predicted operational temperatures. This paper briefly covers the main design features of the radiation cover and measures taken to mitigate risks to cover deployment. As the chosen FD04 model Frangibolt actuator has minimal flight heritage, the main focus of this paper is the testing, results and conclusions with the FD04 while discussing key lessons learned with respect to the use of the FD04 actuator in this application.

Introduction

REXIS is a student collaboration experiment aboard the Origins, Spectral Interpretation, Resource Identification, and Security Regolith Explorer (OSIRIS-REx) spacecraft. OSIRIS-REx is a NASA New Frontiers mission planned for launch in 2016 that will travel to near-Earth asteroid 101955 Bennu and return at least 60 g (0.013 lbm) of asteroid regolith to Earth in 2023. REXIS uses coded-aperture imaging X-ray spectroscopy to image Bennu in the soft X-ray range of 0.5-7.5 keV and develop an elemental abundance map of the asteroid [1]. REXIS is engineered primarily by students, with supervision and support from professional scientists and engineers at the MIT Space Systems Laboratory; MIT Department of Earth, Atmospheric, and Planetary Sciences; Harvard-Smithsonian Center for Astrophysics; the MIT Kavli Institute; MIT Lincoln Laboratories; and Aurora Flight Sciences.

REXIS requires a one-time deployable cover door to protect its charge-coupled device (CCD) imagers from radiation damage during the three-year cruise to Bennu. The door is positioned on top of the instrument and is closed from launch in 2016 until asteroid observation in 2019, at which point the door will be opened, providing the CCDs a view of the asteroid. Without this cover, space radiation will cause displacement damage in the detectors and degrade spectral resolution [2]. Use of a radiation cover will limit damage so that the REXIS detectors can meet measurement objectives in its primary mission phase.

In this paper, we focus on the mechanical design of the radiation cover and the opening mechanism. The 4-mm (0.2-in) thick aluminum (Al) cover rotates about a custom spring hinge and is opened upon arrival at Bennu through the use of an FD04 Frangibolt from TiNi Aerospace, which is part of a newly- introduced Mini Frangibolt family. This family of Frangibolts incorporates cylinders made from Single Crystal Shape Memory Alloy that offer 3 times the stroke performance of equivalent products from the Standard Frangibolt family (FCx). Other advantages of this product are its low power requirement, small form factor, and low cost. However, the Mini Frangibolt product family has minimal flight heritage. Successful actuation of the FD04 Frangibolt is highly sensitive to the thermal and structural design of the bolted joint. Given the minimal flight heritage for FD04, prototype testing of the REXIS radiation cover has focused on establishing confidence in the FD04 Frangibolt mechanism as a reliable actuator for this application and creating a robust design for the radiation cover. This paper presents the overall radiation cover design, provides an overview of the testing performed, and discusses the lessons learned.

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Design Overview

Requirements on the REXIS radiation cover flow from instrument measurement objectives as well as interface and environmental requirements. In order to meet REXIS science goals, the cover must provide a sufficient level of radiation protection for the CCDs. However, as a student instrument, the mass and power available to the REXIS instrument is limited. The “not to exceed” values for REXIS are 6.5 kg (14 lbm) mass and 15 W average power. Therefore a low mass and low power actuation device is desired. During the cruise to the asteroid, REXIS will experience very cold temperatures. All components of the mechanism must be kept warm enough to ensure successful cover opening. Lastly, as an asteroid-sample return mission, OSIRIS-REx has strict contamination requirements. These constraints flow to REXIS, and it is imperative that the opening of the door does not release particulates or molecular contaminates that could endanger the integrity of the asteroid sample.

The REXIS radiation cover is located on top of the instrument and covers the coded-aperture mask so there is no direct line of sight for radiation to impinge on the CCDs. The cover design is shown in Figure 1a in the closed configuration. The 4-mm-thick (0.2-in) aluminum radiation cover rotates about a custom spring hinge with a 3/16-in (4.76-mm) diameter stainless steel shaft. The mechanism rotates about Vespel SP-3 bushings. Additional bushings made of Rulon J are also placed in between the torsion springs and the shaft to reduce friction and prevent cold welding of the springs to the shaft. The door is held in the stowed position by an FD04 Frangibolt actuator and custom notched titanium (Ti) bolt. The FD04 was largely chosen due to its large stroke performance over equivalent products in the Standard Frangibolt family (FCx), along with its low power requirements, low mass, and low cost.

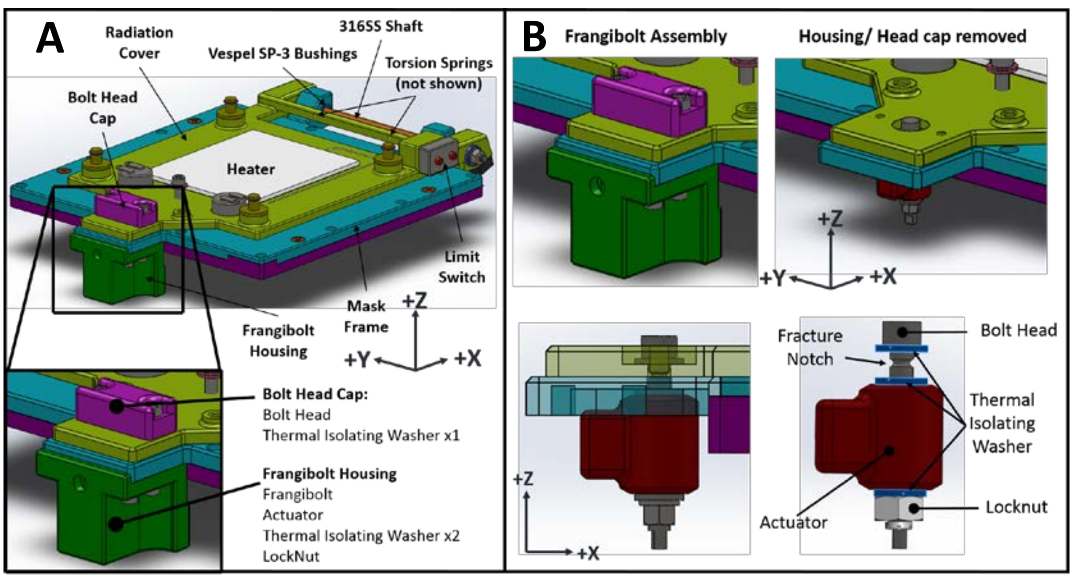

Figure 1. (a) The REXIS radiation cover in closed configuration (b) detail of the Frangibolt assembly

The FD04 is part of the recently introduced Mini Frangibolt product family and has flight heritage on the DICE CubeSat [4]. It consists of a Copper-Aluminum-Nickel shape memory alloy cylinder and provides ~550 lb (2450 N) of force to fracture the fastener in tension during actuation. This model is the smallest in size and requires the least power of the TiNi Frangibolts. It has a compressed length of 0.500 in (12.7 mm), and a stroke of 0.040 in (1.0 mm). Although shorter in length than a typical Nitinol alloy actuator (such as the FC2, which at a length of 1.000 in (25.40 mm) is the next size up), the FD04 has a larger stroke and is therefore less sensitive to preload [3]. The Frangibolt fastens two tabs together, one on the cover and one on the mask frame to hold the door closed. When power is applied to the Frangibolt, an internal heater (with redundant capacity) heats up the memory shape alloy, placing the bolt under tension and causing it to fracture. Once the Ti bolt is fractured, the door is released and opened by stainless steel torsion springs that are wrapped around the hinge. To ensure the door will open, the springs are sized to provide sufficient torque margin to overcome expected resistive torques such as friction in the hinge and the resistance from the flight harness. Throughout cruise, a heater on the radiation cover will keep the Frangibolt assembly and hinge components well above their survival cold temperatures.

The implementation of the FD04 Frangibolt actuator on REXIS includes a custom housing, stiff joint design, and appropriate thermal path. In Figure 1b, the housing is hidden from view to show the Frangibolt stack-up including the bolt, thermal isolation washers, actuator, and locknut. It is important to thermally isolate the FD04 Frangibolt actuator from the surrounding structure in order for the cylinder to reach actuation temperature upon application of power. Custom low-conductivity washers are placed between the FD04 Frangibolt and its surroundings to achieve the required thermal isolation. For the FD04 Mini Frangibolt actuator to operate properly, careful attention must be paid to the fastener and the joint design. A stiff joint design is necessary to ensure that there are no gaps, the joint fits inside the grip length of the fastener, and the fastener is properly torque loaded in order to achieve the required preload. The housing, shown in Figure 1a, is necessary to capture the parts that become free after the bolt fractures. The main Frangibolt housing mounts to the lower tab and contains the Frangibolt actuator, two thermal isolation washers, the lower portion of the bolt, and a locknut that holds everything in place. The top portion, the bolt head cap, fastens to the top tab and retains the head of the fractured bolt as well as one thermal isolation washer.

Test Effort

Prototypes of the REXIS radiation cover were developed, designed, and tested as part of the RE XIS instrument engineering test unit (ETU) effort during the summer and fall of 2013. The main objectives of the REXIS prototype radiation cover testing were to validate the design of the REXIS bolted joint, establish confidence in the reliability of the Frangibolt actuator to operate successfully at predicted temperatures, determine an expected range for actuation times at a given temperature, and gain experience with installation and use of the FD04 actuator. Two prototypes were tested: a smaller ETU-1 model, and a larger ETU-2 model (Figure 2). The ETU-1 design represents an earlier concept that was later updated to a larger design (ETU-2) to accommodate moving the cover from the CCD assembly to the coded-aperture mask.

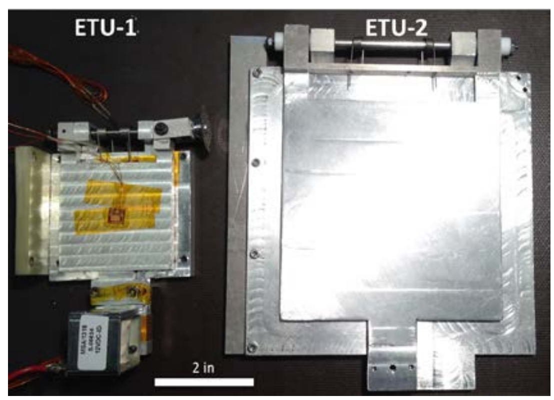

Figure 2. ETU-1 and ETU-2 prototypes

Actuation and deployment of the cover was tested in thermal vacuum (T-Vac) chambers at temperatures as low as -48°C (shown in Figure 3). Each test specimen was mounted to an interface that was conductively cooled with liquid nitrogen. The mechanism was instrumented with resistance temperature detectors (RTDs) to track the temperature history of critical features on the mechanism during testing. Tests were performed with both Ti and G10 fiberglass washers to determine the impact of the washers on the thermal path. Electrical lines were fed through the chamber outside to a workstation, power supply, and multimeter as required. Tests were also performed at both 9 and 10 VDC to assess the impact of input power on actuation time. Power was applied and manually controlled from an external source during testing. In each test, power was applied to the Frangibolt and the actuation times and temperature histories were recorded.

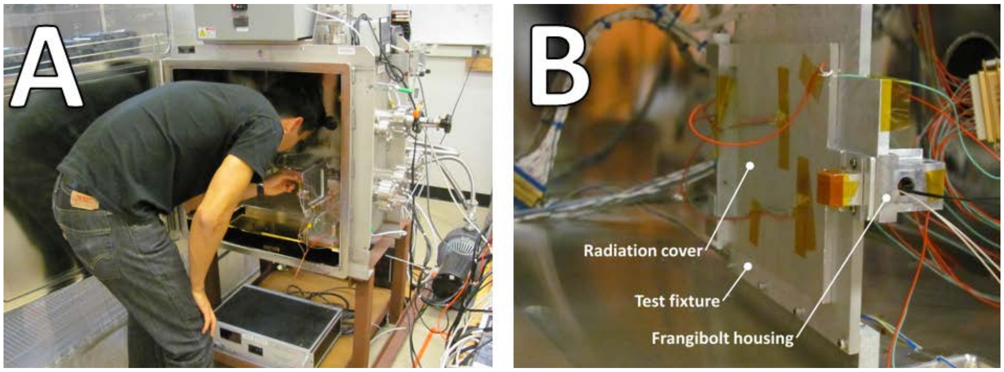

Figure 3. (a) Large T-Vac chamber used for ETU-2 (b) ETU-2 mounted to cold baseplate

Results

The FD04 successfully fractured the fastener and opened the radiation cover in 19 of 22 tests attempted. The tests in which actuation did not occur were all early -20°C attempts before the thermal isolation issues were completely understood. In order not to risk damaging the FD04 Frangibolt, the power to the Frangibolt was shut off at 70 seconds. Once the thermal isolation issues were understood and power was applied for greater duration, the same FD04 Frangibolts actuated successfully. The actuation times for the successful tests can be seen in Figure 4. This figure shows the test temperature and the time required to achieve actuation. In general, we see a trend of longer actuation times with colder temperatures. However, the results also show that at a given temperature, actuation time decreases as the power applied to the FD04 increases. Actuation at -40°C took more than 120 seconds with Ti washers and 9 V. The same test configuration at a similar temperature actuated in only 80 seconds when 10 V was applied. During the testing period, TiNi Aerospace provided the REXIS team with an alternate washer design made from G10 in order to reduce the actuation time at low temperatures. The results show that the use of G10 washers consistently reduces the Frangibolt actuation time when compared to the use of Ti washers at similar temperatures and the same input voltage. Near -40°C and with an input power of 10 V the actuation time was reduced from 80 seconds to 40 seconds by changing from Ti to G10 washers. These results verify expectations based on the thermal conductivities between G10 and Ti and correlate with similar tests performed by TiNi. Finally, one test was performed at a very low preload (torqued to ~0.5 in-lb (0.06 N-m) as opposed to the specified 2.7 in-lb (0.3 N-m)) to confirm that the stroke of the FD04 could fracture the fastener under these conditions. This test was performed with G10 washers at room temperature and with 9 V applied. The fastener broke in less than 20 seconds. As shown in Figure 4, this actuation time is in family with all other room temperature tests conducted with both G10 and Ti washers at the specified installation preload.

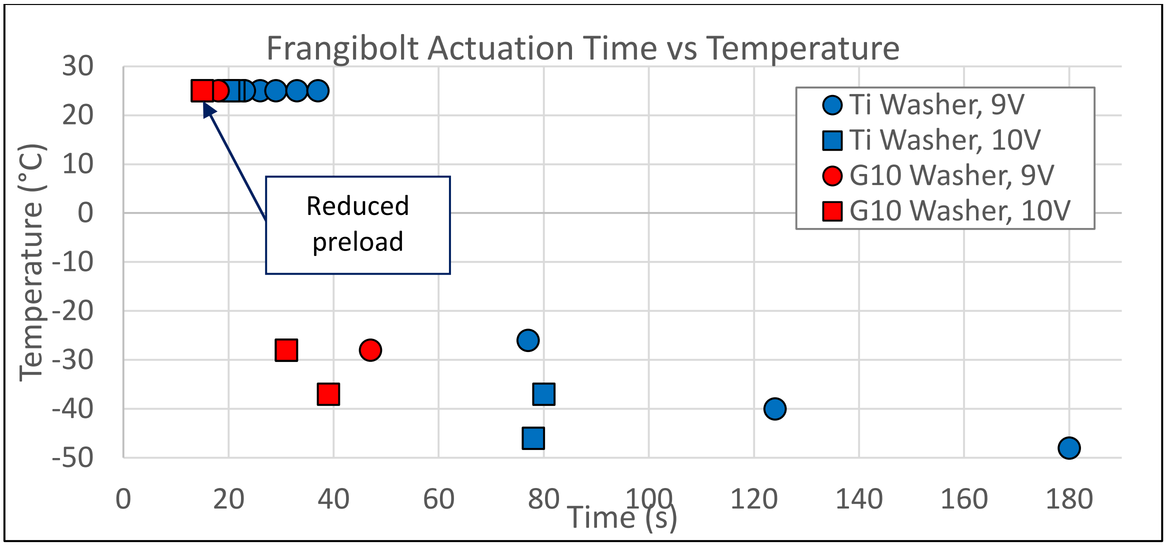

Figure 4. Actuation times for ETU-1 and ETU-2 as a function of temperature

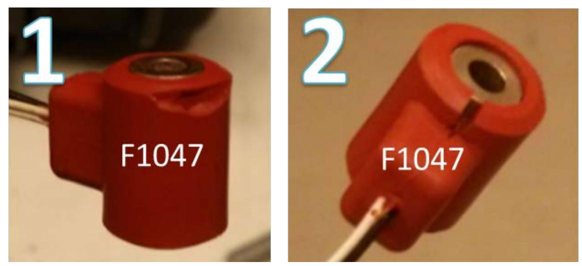

Figure 5. Cosmetic damage to the FD04 jacket post-actuation. The numbers are the actuator serial number.

Despite successful bolt fracture upon Frangibolt actuation, there were a few post-actuation observations worth noting. During the test protocol, four distinct FD04 actuators were used. In the course of testing, the first two actuators developed a tear along the seam of the insulation as shown in Figure 5. In addition, after the change from ETU-1 to ETU-2 a chip was observed in the actuator jacket (also shown in Figure 5). Upon actuation, the FD04 does move significantly, and it is believed that this damage to the Frangibolt jacket was due to impact with the aluminum housing around the Frangibolt. The tearing and damage to the jacket is cosmetic in nature and does not affect the performance of the FD04. Further tests with both actuators resulted in successful cover openings. However, given the strict contamination requirements on OSIRIS-REx it is important to avoid this type of damage to the actuator on REXIS. To mitigate the issue, the Al housing was modified to remove sharp edges, allow more movement clearance for the actuator, and include cushioning. Once these changes were made, no further damage to the jacket occurred.

After two particular tests, the power to the Frangibolt actuator was not cut immediately after actuation and white smoke was observed emitting from the actuator in one of the tests. In these cases the actuators were irreparably damaged. Once the fastener has broken, the FD04 is essentially floating free in the housing and the thermal path to the rest of the structure is broken. In this state, the actuator heats up very quickly and can easily exceed its high temperature limit. The FD04 as designed does not include a temperature sensor. Therefore, a limit switch of some type must be used to confirm actuation and ensure that power is cut.

Discussion and Lessons Learned

The testing of the REXIS radiation cover prototypes validated the functionality of the deployment mechanism. The cover actuated successfully in 19 tests at a range of temperatures from -48°C to 25°C and both in air and in vacuum. It was shown that the springs open the cover once the fastener has fractured and that the cover remains open. It was noted that a large kick-off force is provided by the FD04 actuation, and systems that are sensitive to shock or jitter may require damping. The REXIS radiation cover design was modified to include bumper tabs with Poron 4701-40 to reduce the impact of the door opening. It is important to note that a flight harness will need to pass over the hinge of the door in order to power the radiation cover heater. Testing with an appropriate mockup of this harness in place is planned. The testing also revealed a few lessons learned about working with the FD04 Frangibolt. These lessons include the importance of the thermal isolation of the FD04, the need for additional telemetry to signal actuation and cut power to the FD04, and the need for careful housing design to avoid cosmetic damage to the actuator jacket.

Actuation Time and Thermal Path

As expected, actuation time increases at lower test temperatures. This trend is likely a combination of two phenomena. First, it naturally takes the actuator heater longer to heat the shape-memory alloy to the necessary temperature when starting at colder temperatures. Secondly, at colder temperatures and once the Frangibolt starts heating, there is a greater temperature difference between the Frangibolt and its surroundings. As the heat transfer rate due to conductance is based on the temperature gradient between two surfaces, heat is lost from the Frangibolt to its surroundings at a higher rate when at colder temperatures. This increased heat transfer rate and demand for heat directly correlates to an extended amount of time power must be applied to achieve the necessary stroke on the actuator to fracture the bolt. Therefore, the specific structural/thermal path within the Frangibolt mechanism directly impacts this temperature vs. actuation time relationship. Testing has shown that the use of G10 washers and the application of 10V both significantly reduce the actuation time at low temperature. The G10 washers better thermally isolate the actuator, allowing for quicker actuation when compared to the Ti washers and the increase in input power allows the heater to come to temperature more quickly.

The use of G10 washers raises several questions and potential issues, however. The heater installed on the radiation cover is meant to ensure the Frangibolt mechanism stays above survival temperatures during its cruise to Bennu. A trade exists between power allocation and actuation time. On the one hand, good thermally isolating washers such as G10 will enable a quick and efficient actuation. On the other, they make it more difficult for the heater to keep the Frangibolt warm during cruise and therefore demand a larger power allocation from the spacecraft. There was an additional concern that G10 washers may reduce the preload of the Frangibolt at actuation. As G10 is a much softer material than Ti, it is unknown whether compression under long periods of time will cause the washer material to creep and cause the bolt to lose its desired installation preload. However, due to the large stroke on FD04, there is a significant margin of safety against bolt preload, such that the Frangibolt should be able to actuate even with zero installation preload. A test was performed successfully with G10 washers and significantly reduced preload (test annotated in Figure 4) to verify the insensitivity of the FD04 to preload.

Application of Power Post-Actuation

Once the bolt breaks, there is no longer a thermal path or heat sink to absorbs heat from the actuator. Therefore, if power is applied to the FD04 actuator post actuation, the shape-memory alloy can overheat and outgas. With strict outgassing and contamination control requirements in place, REXIS must ensure that its operations do not contaminate the regolith sample collected by OSIRIS-REx. Unlike other Frangibolt models, the FD04 does not have an internal temperature sensor. For this reason, it is not possible for REXIS to prevent overheating by monitoring the Frangibolt temperature and control power based on this temperature. REXIS must incorporate additional hardware and software modifications as a means to determine successful actuation. One solution is to incorporate a limit switch that is compressed when the door is closed and released when the cover opens. This switch is constantly monitored by the instrument's main electronics board and allows for immediate power cutoff upon Frangibolt actuation.

There is some coupling between the actuation time and the concern of power post-actuation. While it is not necessary for REXIS to experience short actuation times, it has been found that longer actuation times result in a greater uncertainty of actuation time. There is more spread in the data at colder temperatures because small differences between tests amplify over time. The faster the Frangibolt can be actuated, the greater certainty there is that it will do so closer to an expected time. Since failure to cut power to the actuator within several seconds after actuation can potentially cause outgassing issues, it is crucial that the actuation time for the Frangibolt be characterized and fully understood.

Through the performed tests, we have seen significant differences in actuation times between tests with 9 and 10 VDC applied to the Frangibolt actuator. This result can be attributed to two factors. By observing the electrical power equation ($P = \frac{V^2}{R}$), one can see that an increase in voltage has a squared effect on the power applied. Therefore, a change from 9 to 10 VDC has a large impact on how quickly the Frangibolt heats. Secondly, the faster the Frangibolt can be heated to its actuation temperature, the less time there is available for heat to be lost to the environment.

Housing Design

Testing showed that there is a significant kickoff force caused from bolt fracture. This force can cause damage to the actuator insulation if allowed to impact edges of the housing, as was observed. Care must be taken to ensure any Frangibolt housing design will provide clearance to the actuator and not cause damage from the reaction of the actuation. Figure 6 shows some of the features made in the housing to provide freedom of movement for the actuator. It was noticed that during actuation the heater wires that exit the housing were impacting the edge of the existing cut, causing the actuator to twist and inadvertently impact other edges. The slot shown in Figure 6b was extended so that the wires did not catch upon actuation and cause damage. Additionally, all sharp edges were filed as to avoiding cutting of the actuator jacket. The addition of cushioning to the inside of the actuator housing is another way to mitigate this issue. Although the tearing of the jacket does not impact the performance of the FD04, it was found that resetting the FD04 and subsequent actuations do cause tearing to propagate. Therefore, the actuator should be carefully inspected before and after each test.

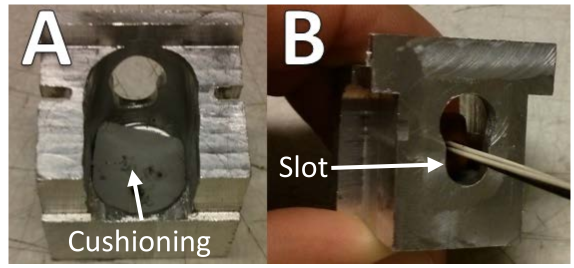

Figure 6. Frangibolt housing shown with features used to avoid actuator damage

Conclusion

Overall, testing of the radiation cover prototypes and Frangibolt implementation provided valuable insight, considerable knowledge, and a number of lessons learned regarding the thermal and mechanical sensitivity of the FD04 Frangibolt actuator. The prototype cover successfully opened 19 times at a range of temperatures. It was confirmed that a clear relationship between actuation time and testing temperature exists and is closely related to the established thermal path. Lessons were learned about implementing the FD04 on an instrument like REXIS. The power applied has a strong impact on actuation time. Likewise, if power is applied to the Frangibolt post-actuation the heater can burn and smoke, causing outgassing and contamination issues. The insulating jacket on the space-rated FD04 actuators is sensitive to impact so any housing around the actuator must be designed with that point in mind. The REXIS ETU radiation cover design and test enabled characterization of this mechanism within the relevant environments, and the lessons learned from these efforts will form the basis for a robust flight model radiation cover design.

Acknowledgements

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